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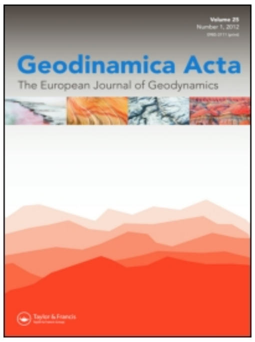

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Palaeozoic-Recent geological development and uplift of the Amanos Mountains (S Turkey) in the critically located northwesternmost corner of the Arabian continent

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ABSTRACT
We have carried out a several-year-long study of the Amanos Mountains, on the basis of which we present new sedimentary and structural evidence, which we combine with existing data, to produce the first comprehensive synthesis in the regional geological setting. The ca. N-S-trending Amanos Mountains are located at the northwesternmost edge of the Arabian plate, near the intersection of the African and Eurasian plates. Mixed siliciclastic-carbonate sediments accumulated on the north-Gondwana margin during the Palaeozoic. Triassic rift-related sedimentation was followed by platform carbonate deposition during Jurassic-Cretaceous. Late Cretaceous was characterised by platform collapse and southward emplacement of melanges and a supra-subduction zone ophiolite. Latest Cretaceous transgressive shallow-water carbonates gave way to deeper-water deposits during Palaeocene-Eocene. Eocene southward compression, reflecting initial collision, resulted in open folding, reverse faulting and duplexing. Fluvial, lagoonal and shallow-marine carbonates accumulated during Late Oligocene(?)-Early Miocene, associated with basaltic magmatism. Intensifying collision during Mid-Miocene initiated a foreland basin that then infilled with deep-water siliciclastic gravity flows. Late Miocene-Early Pliocene compression created mountain-sized folds and thrusts, verging E in the north but SE in the south. The resulting surface uplift triggered deposition of huge alluvial outwash fans in the west. Smaller alluvial fans formed along both mountain flanks during the Pleistocene after major surface uplift ended. Pliocene-Pleistocene alluvium was tilted towards the mountain front in the west. Strike-slip/transtension along the East Anatolian Transform Fault and localised sub-horizontal Quaternary basaltic volcanism in the region reflect regional transtension during Late Pliocene-Pleistocene (<4 Ma).

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Neotethys; Easternmost Mediterranean; Amanos Mountain; Southern Turkey

1. Introduction

The Tethys ocean has dominated the geology of the Eastern Mediterranean region. Specifically, the Southern Neotethys was bordered by North Africa, southern Greece and southern Turkey and extended eastwards though Iran (Barrier & Vrielynck, 2009; Robertson & Dixon, 1984; Robertson, Parlak, & Ustaömer, 2012; Şengör & Yılmaz, 1981). This ocean basin is known to have developed through a series of discrete tectonic stages, including pre-Triassic platform, Triassic rift basin, Jurassic-Cretaceous passive margin, Late Cretaceous supra-subduction zone ophiolite (exposed oceanic crust) genesis and emplacement and Neogene collision, culminating in final emplacement and surface uplift. Much research has focussed on the allochthonous units that resulted from closure of the Southern Neotethys, as exemplified by the Taurus Mountains of southern Turkey (Figure 1). However, there is relatively little evidence from the underlying Africa-Arabian plate, mainly because this still lies beneath the deep sea in the easternmost Mediterranean or is poorly exposed within the suture zone in SE Turkey (Figure 1). One area where the lower plate is regionally exposed is the Amanos Mountains, although this region has largely escaped attention in the recent discussion of the Taurus Mountains and their uplift. The main reasons for this are its large size, relative inaccessibility, geological complexity and low-grade metamorphism that affects pre-late Mesozoic lithologies.

In this paper, backed by extensive fieldwork over several years, we provide the first comprehensive description and multi-disciplinary synthesis of the Amanos Mountains in their regional tectonic context. We will show how the geology of the Amanos Mountain region relates to successive stages of development of the Southern Neotethys, including pre-rift, rift, passive margin, ophiolite genesis and emplacement, collision and uplift. Our new evidence

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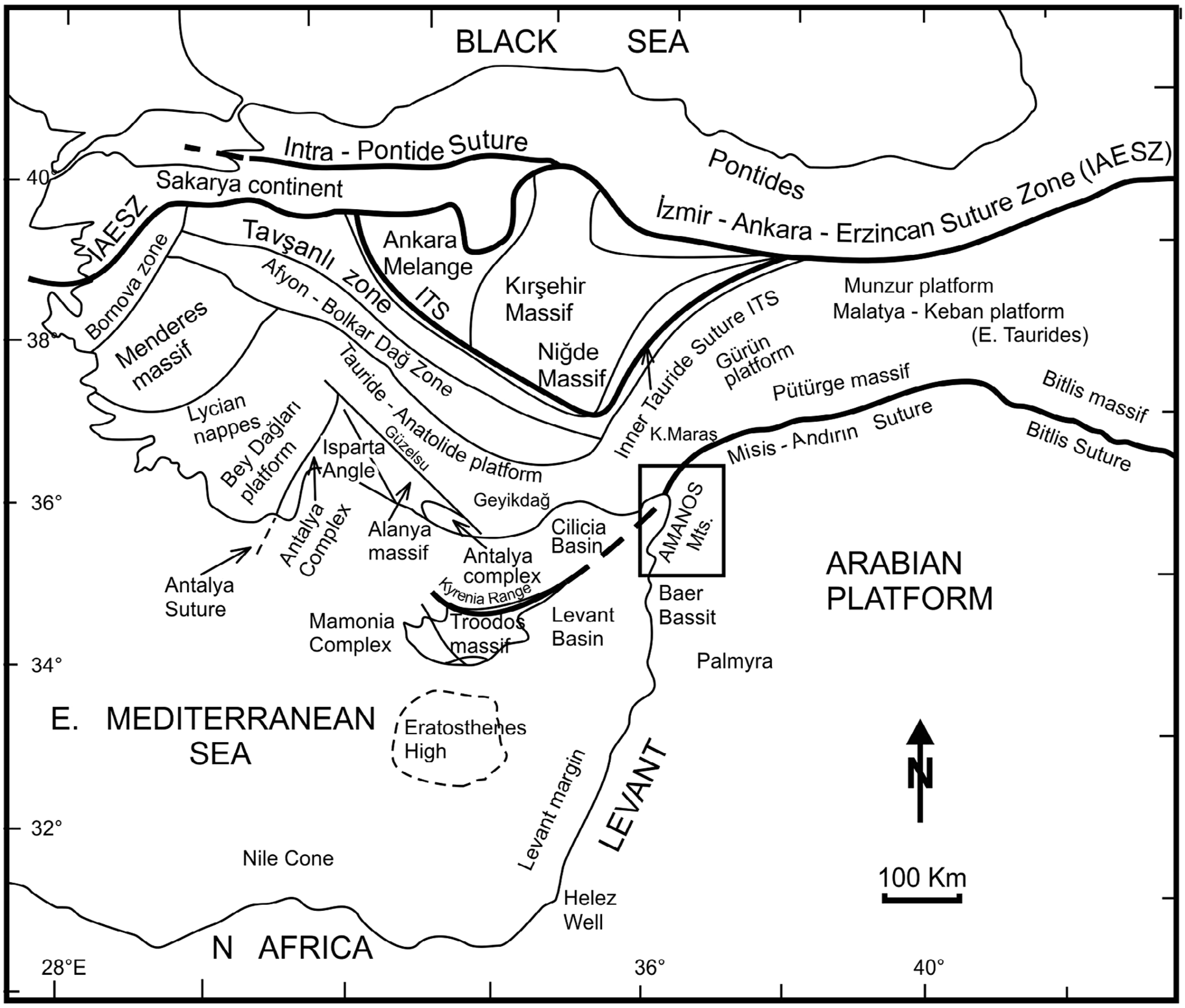

Figure 1. Tectonic zones of Turkey. The study area is marked by the box. Main data source: 1:500,000 Geological Map of Turkey (Şenel, 2002). Note the critical location at the northwestern corner or the Arabian platform. Source: Authors

also contributes significantly to the current debate concerning the timing and processes of mountain uplift in the Eastern Mediterranean region (Cosentino et al., 2012; Palamakumbura et al., 2016; Schildgen, Cosentino, Bookhagan et al., 2012), and other areas including Iran (Agard, Omrani, Jolivet, & Mouthreau, 2005), the Himalayas (e.g. An, Kutzbach, Prell, & Porter, 2001; Clark et al., 2005), the Andes (e.g. Gregory – Wodzicki, 2000; Marquardt, Lavenu, Ortleib, Godoy, & Comte, 2004) and the European Alps (e.g. Brückl et al., 2007; Persaud & Pfiffner, 2004; Schlunegger & Matthias, 2001; Wagner et al., 2010). Our study builds on previous geological studies of the Amanos Mountains (both published and unpublished) that mostly relate to fieldwork during the 1980s.

The Amanos Mountains trend ca. NNE-SSW in contrast to the adjacent Taurus Mountain lineament which is orientated more NE-SW; this suggests a contrasting tectonic development. The Amanos Mountains are located along the northwestern margin of the Arabian plate, directly north of the eastward termination of the Mediterranean Sea and the Levant rifted continental margin (Figures 1 and 2). The Amanos Mountains lie within an oroclinal bend where the Taurus mountain front bends from ca. E-W to more NNE-SSW (Figure 2). The mountains are specifically located at the interface between the central and eastern segments of the Taurus Mountains, close to the triple junction between the Arabian, African and Eurasian plates (e.g. Gülen, Barka, & Toksöz, 1987; Karig & Kozlu, 1990; McKenzie, 1976; Perinçek & Çemen, 1990; Westaway, 2004). This mountainous region encodes much critical evidence concerning Tethyan evolution which is explored here.

The Amanos Mountains are elongate, extending for ca. 170 km longitudinally, with a width of ca. 40 km in the north, decreasing to ca. 20 km in the south. They reach a maximum height of 2262 m on Bozdağ in the centre of the range (Hassa area), and then generally decrease in altitude southwards until they merge with the regional topography of the Arabian plate (Figure 3). The range is asymmetrical, with the eastern flank being narrower and steeper than the western flank. The eastern flank is paralleled by the neotectonic East Anatolian Transform Fault (EATF) and the tectonically controlled Karasu Valley, with the Hatay graben to the south. The western Amanos

Mountain flank is bordered to the north by the intermontane K. Maraş Basin and to the west by the contiguous Ceyhan Basin, which extends offshore into the Cilicia Basin. In the southwest, the mountain range is separated from the Gulf of İskenderun by a narrow coastal plain. For ease of description here, we loosely divide the Amanos Mountains into northern, central and southern areas and we commonly compare the eastern and western flanks.

2. Objectives and methods

This paper focusses on the following main aspects: (1) the Palaeozoic-Mesozoic geological development and rifting of Neotethys; (2) the role of Tethyan ophiolite and melange emplacement; (3) the Paleogene-Neogene sedimentary development; (4) the nature and timing of formation of structures on all scales; (5) Pliocene-Pleistocene syn-tectonic sedimentation and deformation; (6) the relation of the Amanos Mountains to the Arabian platform (to the south) and also with the central and eastern Taurides (generally to the north; Figure 1).

We will first summarise and interpret the geological development utilising a series of time slices, with emphasis on the Mesozoic to Recent Tethyan and post-Tethyan development. Then we will discuss the key structural features and the Neogene-Recent tectonic development. All of the available information will then be synthesised, particularly with a view to evaluating the timing and processes of uplift of the Amanos Mountains in their regional context.

During our fieldwork (2013–2016), we have obtained the following main types of new data for the Amanos Mountains and its peripheral region. (1) Stratigraphical and sedimentological observations of sedimentary units of all ages throughout the region, allowing the first interpretation of sedimentary processes affecting the area; (2) Measurement and interpretation of geological structures of all scales throughout the region, including folds, thrusts, normal faults and strike-slip faults. We highlight the importance of regional thrusting in the emplacement of the ophiolitic rocks and related melanges and we identify the importance of Neogene mountain-scale folding in the uplift of the mountains; (3) Observations and preliminary interpretation of Neotectonic and geomorphological features including Plio-Pleistocene clastic sediments, tilted fluvial terraces, erosion surfaces and drainage patterns, based on field observations and remote sensing. Throughout, we build-on and integrate existing geological information, especially from geological mapping on regional to local scale, especially from Yalçın (1980), Yılmaz (1984), Önalan (1986) and Ulu (2002a, 2002b). We utilise the map patterns and outcrop relations of the sedimentary, igneous and metamorphic lithologies, mainly with a view to understanding tectonic processes and events. We have also carried out reconnaissance studies of the Arabian platform to the NE of the Amanos Mountains and we combine this with published information on the central and eastern Taurides to produce an overall interpretation, which we hope will stimulate future research in this fascinating region.

In the text of our paper below, we highlight our main observations and interpretations. To support these we make available much associated data in an extensive electronic supplement, which includes: (1) Field photographs of Palaeozoic-Mesozoic (12 photos, Figure 1Ⓔ), Eocene-Miocene (12 photos, Figure 2Ⓔ) and Pliocene-Quaternary (8 photos, Figure 3Ⓔ)sedimentary features; (2) Field photographs of outcrop-scale structural features such as shear bands, asymmetrical S-type folds, isoclinal folds, sheared pebbles (16 photos, Figure 4Ⓔ) and faults (3 photos, Figure 5Ⓔ); (3) Field photographs showing lithological and structural influences on geomorphology (Figure 6Ⓔ); (4) Our complete structural database (327 measurements) including kinematic measurements of 168 beddings, 47 schistosities, 88-fold axis and 240 fault orientations (Table 1Ⓔ); (5) Microfossil dating (7 thin sections) of critically positioned limestones (Table 2Ⓔ).

In the paper, we use the time scale of Gradstein, Ogg, Schmitz, and Ogg (2012).

3. Stratigraphical setting

The geological record of the Amanos Mountains encompasses Cambrian to Recent, as shown on MTA 1:500.000-scale maps (Ulu, 2002a, 2002b; see Electronic Supplement Figures 1–3 for photographs of key sedimentary features). The base of the succession ('Infra-Cambrian)' remains undated. The Palaeozoic-Mesozoic sedimentary lithologies are mostly metamorphosed under greenschist facies conditions (Duman, 1993; Yılmazer & Duman, 1997), as supported by optical petrography and whole-rock X-ray diffraction during this work, which indicates the widespread occurrence of metamorphic textures and minerals (e.g. muscovite, biotite) which are of metamorphic rather than detrital origin.

Unsurprisingly, the biostratigraphic record is sparse compared to that of equivalent but less metamorphosed sequences elsewhere along the northern margin of the Arabian plate. The Palaeozoic-Mesozoic lithologies expose pre-Miocene cover units only in the southern Amanos Mountains (Figure 3). The overall tectono-stratigraphy is strongly influenced by the emplacement of ophiolitic rocks. Previous studies described 13 different ophiolites and related outcrops of melange with numerous different local names (Yalçın, 1980; Yılmaz, 1984). Comparisons of many of the ophiolite outcrops during this work allow these to be correlated as a single regionally emplaced body of rocks which we term the Amanos ophiolite. Latest Cretaceous and Paleogene cover units are widely exposed in the central and western mountain areas. Pliocene deposits occur along parts of the western flank of the range, and Pleistocene deposits

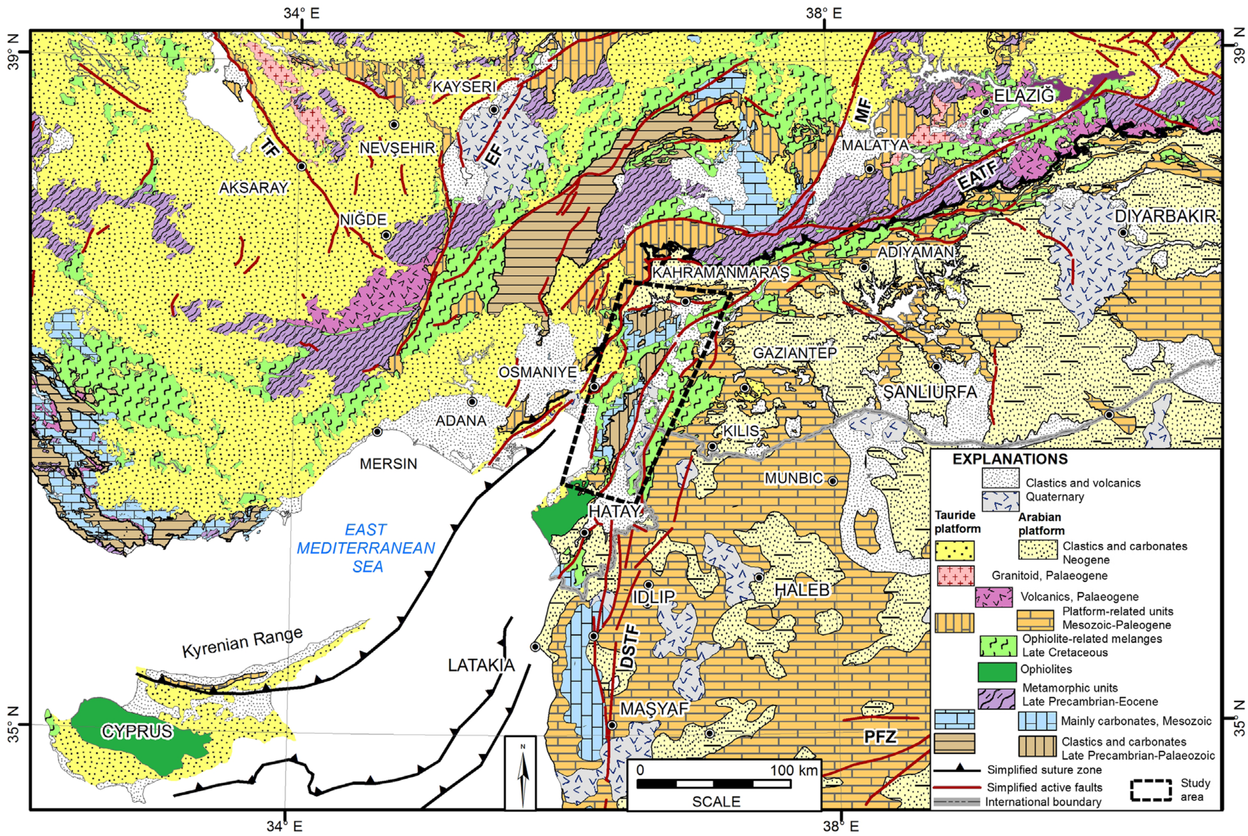

Figure 2. Regional tectonic map showing the main ages and tectonic features of the region surrounding the Amanos Mountains (boxed area). Modified from the 1: 500,000 scale Geological Map of Turkey (Şenel, 2002) and the Geological Map of Syria (Ponikarov & Mikhailov, 1986). Abbreviations: TF, Tuzgölü Fault; EF, Ecemiş Fault, MF, Malatya Fault; EATF, East Anatolian Transform Fault; DSTF, Dead Sea Transform Fault. Source: Authors

are widely distributed on both flanks of the range. Places mentioned in the text below are shown in Figure 3.

3.1. *Palaeozoic: shelf sedimentation*

The oldest rocks are extensively exposed in the northern and central mountains and along the mountain axis in the south (Atan, 1969; Önalan, 1986; Yalçın, 1980; Figures 3 and 4). The Palaeozoic units were investigated throughout the northern Amanos Mountains (e.g. Ceyhan and Sabunsuyu rivers valleys, east of Düziçi and also in the Bahçe, İslahiye and Hassa areas) (Figure 3). All of these rocks have undergone greenschist facies metamorphism (Duman, 1993; Ulu, 2002b). However, the original sedimentary textures are still clearly visible so that we typically refer to e.g. meta-sandstones, meta-limestones, shales etc.

The oldest known sedimentary rocks (Figure 4) are dominated by siliciclastic deposits, which are likely to be of Early Cambrian or possibly even latest Precambrian age ('Infra-Cambrian') based on comparisons with the Arabian platform (e.g. Penbegli-Tut area; Dean & Krummenacher, 1961; Dean, Monod, & Perinçek, 1981). Commonly developed normal-graded bedding, parallel lamination, micro-cross lamination and small-scale scour structures suggest that the earliest known deposition was dominated by gravity-flow processes, although it cannot be excluded that some of these structures could reflect storm activity under shelf-depth conditions. After a reported discordance (Yalçın, 1980) (Figure 4), the succession continues with meta-quartzose, sandstones and dark-coloured, organic-rich shales that are intercalated with carbonate-rich sediments (including dolomites) that include Cambrian trilobites (Dean et al., 1981). There is an upward transition to shelf-type siliciclastic sediments, of inferred Ordovician age, based on trilobite trace fossils (e.g. *Cruziana*) (Dean & Monod, 1985). Siliciclastic intercalations above this occasionally contain Silurian brachiopods (Lahner, 1972).

Following the Late Precambrian Panafrican orogeny, siliciclastic sediments accumulated widely on the Arabian platform as a single mega-sequence of Cambrian to Devonian age (e.g. Wehrmann et al., 2010). The Ordovician to Devonian sediments accumulated on a slowly subsiding shelf along the northern margin of Gondwana, during a time when the dominant control of deposition is likely to have been eustatic sea level change (Mackintosh & Robertson, 2013). The Cambrian sequence is similar in sedimentary facies and thickness to deposits of the same age elsewhere on the Arabian platform, where relatively proximal shelf and platform deposits are exposed (Önalan, 1986), including SE Turkey, Jordan, Lebanon, northwest Saudi Arabia and Iran. In contrast, the Ordovician to Devonian sequence is more similar to that exposed in the Taurides as it is dominated by open-shelf siliciclastic

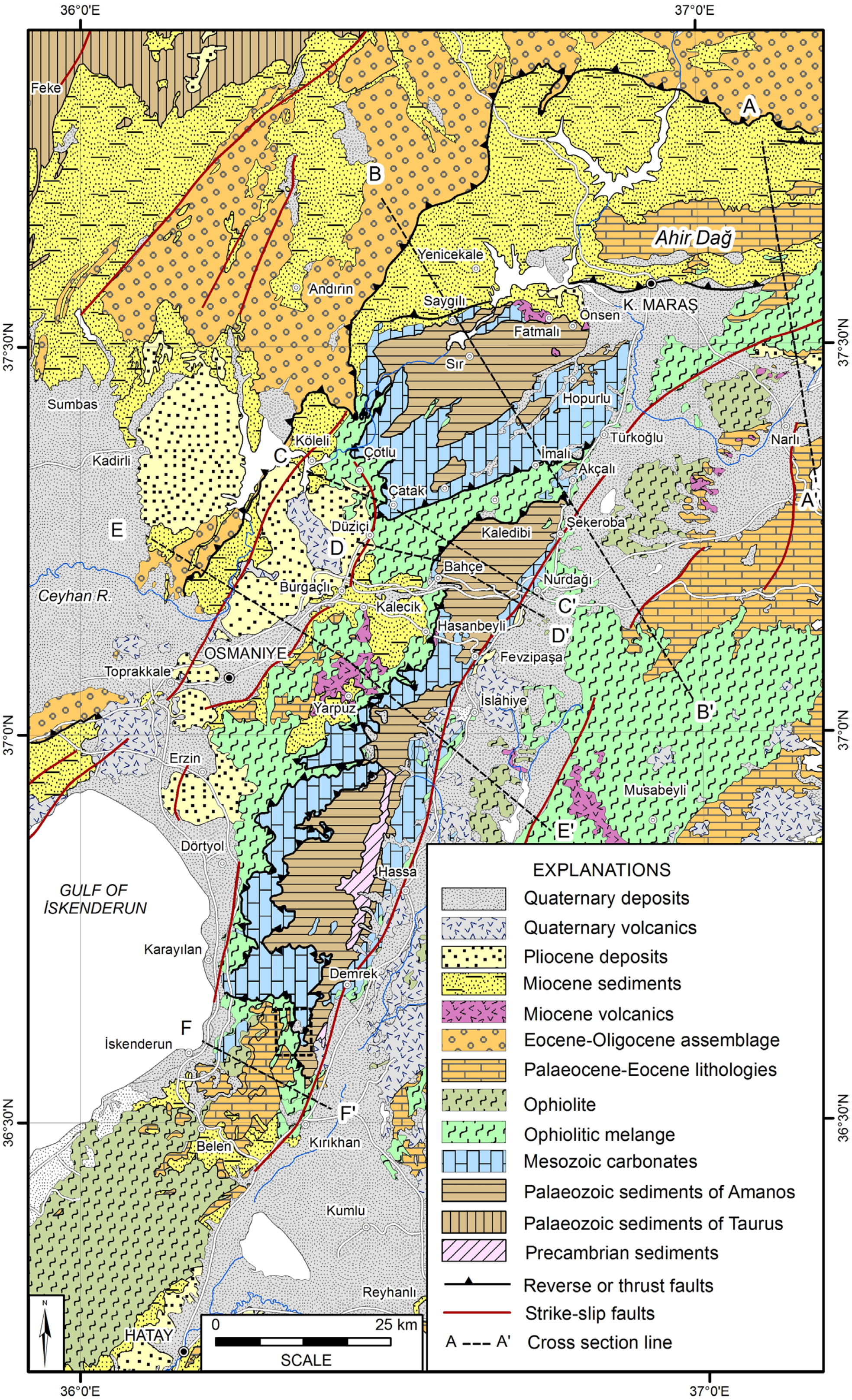

Figure 3. Outline geological map of the Amanos Mountain area, adapted from the 1:500,000 scale geological map of Hatay Region (Ulu, 2002a, 2002b). Source: Authors

sediments and carbonate rocks (Özgül, 1976, 1983, 1984). The Tauride units as a whole reflect shelf deposition along the northern margin of Gondwana (Mackintosh & Robertson, 2013). A switch from a Gondwana-type sequence to a Tauride-type sequence is suggestive of regional subsidence and southward progradation of relatively distal sedimentary conditions.

3.2. Triassic-Cretaceous sequence: South Neotethyan continental margin

The Palaeozoic sequence is transgressed by a Triassic to Late Cretaceous mega-sequence (ca. 2000 m thick) that is exposed on both flanks of the Amanos Mountains (Figures 3 and 4). A similar sequence is also exposed

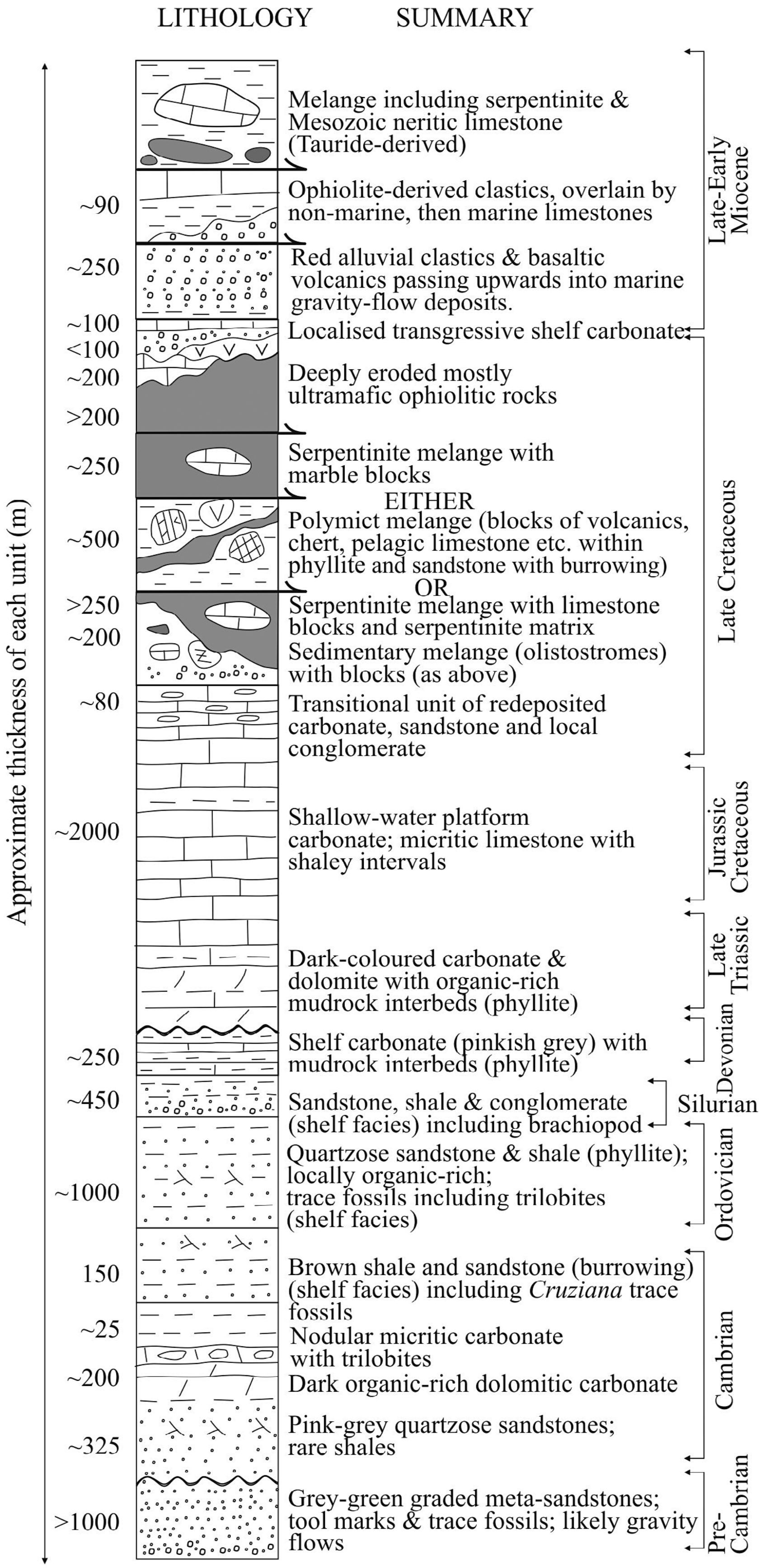

Figure 4. Summary sedimentary log of the main lithological units exposed in the Amanos Mountains. Main data sources: Önalan (1986), Yalçın (1980), 1:500,000 scale map of Hatay Region (Ulu, 2002a, 2002b) and this study.

in the far south of the region (Keldağ Massif, SE of Iskenderun), where the facies are better preserved and well dated (Yılmaz, 1984). The succession exposed on the flanks of the Amanos Mountains begins with alternations of limestone, dolomite, quartzite and black organic-rich phyllite (mudrock). These sediments are inferred to be

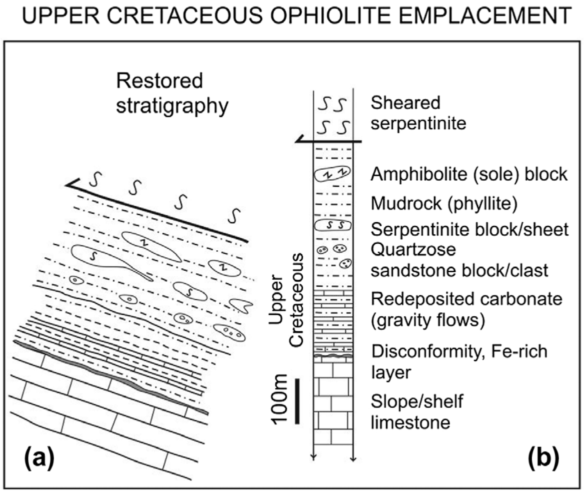

Figure 5. Upper Cretaceous ophiolite emplacement. Stratigraphy (a) and log (b) of the Late Cretaceous platform to melange transition, as exposed in the İmalı area, SW of Türkoğlu, NE Amanos Mountain area.

Late Triassic, based mostly on large bivalves and benthic foraminifera (Aksay, Tekeli, Ürgün, & Işık, 1988; Atan, 1969; Yılmaz, 1984). The sequence continues with shelf-type micritic carbonates, including shaly and bituminous interbeds that are locally dated as Early Jurassic to Early Cretaceous in age, based on a sparse assemblage of benthic foraminifera (Aksay et al., 1988).

We studied the Triassic sedimentary record particularly in the northern Amanos Mountains (e.g. Önsen, Fatmalı, Sır area) and in the central-eastern area (e.g. along the highway from Bahçe to Nurdağı) (Figure 3). The succession typically begins with pebbly conglomerate, interbedded with sandstone and mudrock. Clasts are sub-rounded, to rounded and the conglomerate fabric ranges from clast-supported to matrix-supported. The

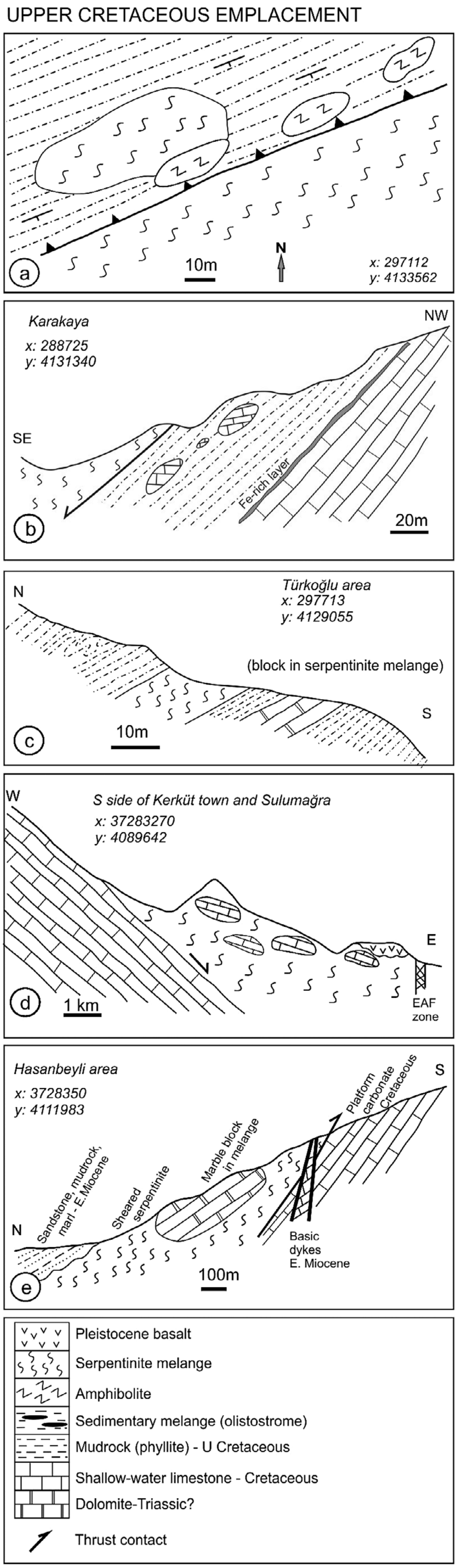

Figure 6. Local sketch map (a) and cross sections (b) of latest Cretaceous emplacement-related features especially the platform to melange transition, as summarised in Figure 5. Details: a, Sketch map of the uppermost part of the platform succession which includes detached blocks, serpentinite and rare amphibolite (disrupted ophiolite metamorphic sole) within sheared mudrock (phyllite); SW of Türkoğlu, NE Amanos Mountain area. (b) Neritic limestone passing upwards into mudrock (phyllite) with limestone blocks, then overthrust by sheared serpentinite, Karakaya; same area as (a); (c) Limestone and serpentinite within sheared mudrock, interpreted as blocks within Late Cretaceous foredeep; same area as (a); (d) Platform limestone overthrust by sheared serpentinite with limestone blocks; Sulumağara, S side of Kerküt town, central eastern flank of Amanos Mountains; (e) Neritic platform carbonates, overthrust by sheared serpentinite with limestone blocks. Transgressive Early Miocene sediments and basaltic dykes are also present. Hasanbeyli area, central northern Amanos Mountain area.

clasts were mostly derived from lithologies exposed within the underlying Early Palaeozoic sequence, especially quartzose sandstone. The succession passes upwards into dark meta-carbonate rocks, pale fossiliferous limestones and black phyllite. Some of the limestones are highly bioclastic and contain bivalves, coral and calcareous algae. The micritic carbonates locally include evaporitic bird's eye structure.

The Triassic sequence reflects tectonic subsidence and associated marine transgression that affected many areas of the easternmost Mediterranean related to rifting of the Southern Neotethys (e.g. in SE Turkey; N Syria, W Cyprus and Antalya region; Garfunkel, 1998, 2004; Robertson et al., 2012; Robertson, Parlak et al., 2016). The Amanos Mountain area was located well south (up to ca. 100 km) of the locus of rifting, such that there is little evidence of strong subsidence, deep-sea sedimentation or volcanism, as observed in areas that were closer the locus of continental breakup (now lost or in over-riding units).

The post-Triassic Mesozoic succession (up to several kilometres thick) is dominated by medium to thick-bedded meta-carbonate rocks with some shaly interbeds; these are equivalent to the Mardin Group throughout SE Turkey (Yılmaz, 1993; Robertson, Boulton et al., 2016 and references). The meta-carbonate rocks are mainly medium to thick-bedded neritic carbonates, which are at least partially recrystallized. Some intervals are very fossiliferous and include corals, calcareous algae, pelecypods and echinoderms. The facies and fossil evidence suggest that the deposition was mainly in a shallow-water shelf setting, punctuated by local emergence. Deposition was accompanied by tectonic subsidence that characterises all of the carbonate platforms bordering the Southern Neotethys during their post-rift passive margin phase (e.g. Sharland et al., 2001; Ziegler, 2001; Ziegler, Cavazza, Robertson, & Crasquin Soleau, 2001). Our interpretation is supported by new observations in several areas: in the northern mountains (e.g. Sır area), in a high-mountain area (E of Düziçi), in the Ceyhan River Valley, in an NE-SW-trending elongate belt (between İmalı and Türkoğlu), along the eastern flank of the mountains (Nurdağı-Fevzipaşa-Hasanbeyli areas), and along the central western flank (near Bahçe) (Figure 3; see also the electronic supplement).

3.3. Late Cretaceous sequence: collapse of the carbonate platform

The intact shallow-water platform succession ends with a distinctive limestone-mudrock interval, up to several hundred metres thick (Figure 5), which is well exposed in several areas (e.g. Imalı-Türkoğlu area (Figure 6(c)), E of Düziçi; Hasanbeyli area, between Fevzipaşa and Nurdağı). These sedimentary rocks are generally less recrystallized than the underlying carbonate platform sequence. In some places, the contrasting deposition begins with one, or several, thin reddish layers that are rich in ferric oxide (Figure 6(b)). Rudist bivalves (Late Cretaceous) are locally present and some horizons are rich in nodular chert of diagenetic origin. Thin to medium-bedded, graded calcarenites appear above this, interbedded with calcareous mudrock (calc-phyllite) (Figure 6(b)). Above come matrix-supported carbonate conglomerates that are interbedded with graded calcarenite. There is also evidence of slumping and soft-sediment deformation. The carbonate material is similar to that within the underlying carbonate platform sequence. This is then an incoming of finely laminated, brownish mudrock (shale/phyllite), with local sandstone interbeds (Figure 5). This interval is similar to the Kastel Formation throughout SE Turkey (Yılmaz, 1993), which is dated as Campanian-mid Maastrichtian in age (Robertson, Boulton et al., 2016).

The varied Late Cretaceous succession is interpreted as the result of flexural collapse of the regional carbonate platform to form a foredeep. This developed as a precursor to the emplacement of melanges and ophiolitic rocks (Figure 7). The initial ferruginous interval (Figure 6(b)) may represent a hiatus in sedimentation, as recorded elsewhere around the periphery of the Arabian platform (e.g. Wasia-Aruma break in Oman; e.g. Glennie et al., 1973; Robertson, Kemp, Rex, & Blome, 1990). As it subsided, the platform tilted to form a carbonate ramp on which bioclastic calciturbidites and carbonate debris-flow deposits accumulated. The resulting deeper waters were productive biologically, hence the occurrence of silica-rich sediment that was transformed to nodular chert during diagenesis. With further subsidence, the platform collapsed to form chaotic debris-flow units and slumped units (up to 10s of metres thick). Similar carbonate platform collapse took place prior to ophiolite emplacement in other peripheral areas of the Arabian platform, notably in Oman (e.g. Robertson, Blome et al., 1990; Robertson, Kemp et al., 1990).

3.4. Amanos ophiolite and related melanges: oceanic crust emplacement

Ophiolite-related rocks in the Amanos Mountain area can be subdivided into four different types of melange and broken formation in different areas of the Amanos Mountains. All of these units are rarely exposed in single outcrops (Figure 7), although an overall tectono-stratigraphy can be inferred based on lateral comparison and correlation. The 1:500,000-scale map of Turkey (Ulu, 2002a, 2002b) distinguishes regionally between intact ophiolite and melange, both of inferred Late Cretaceous age. However, these two different units have not yet been systematically mapped in the Amanos Mountain region, largely reflecting inaccessibility and the dense forest cover in many areas.

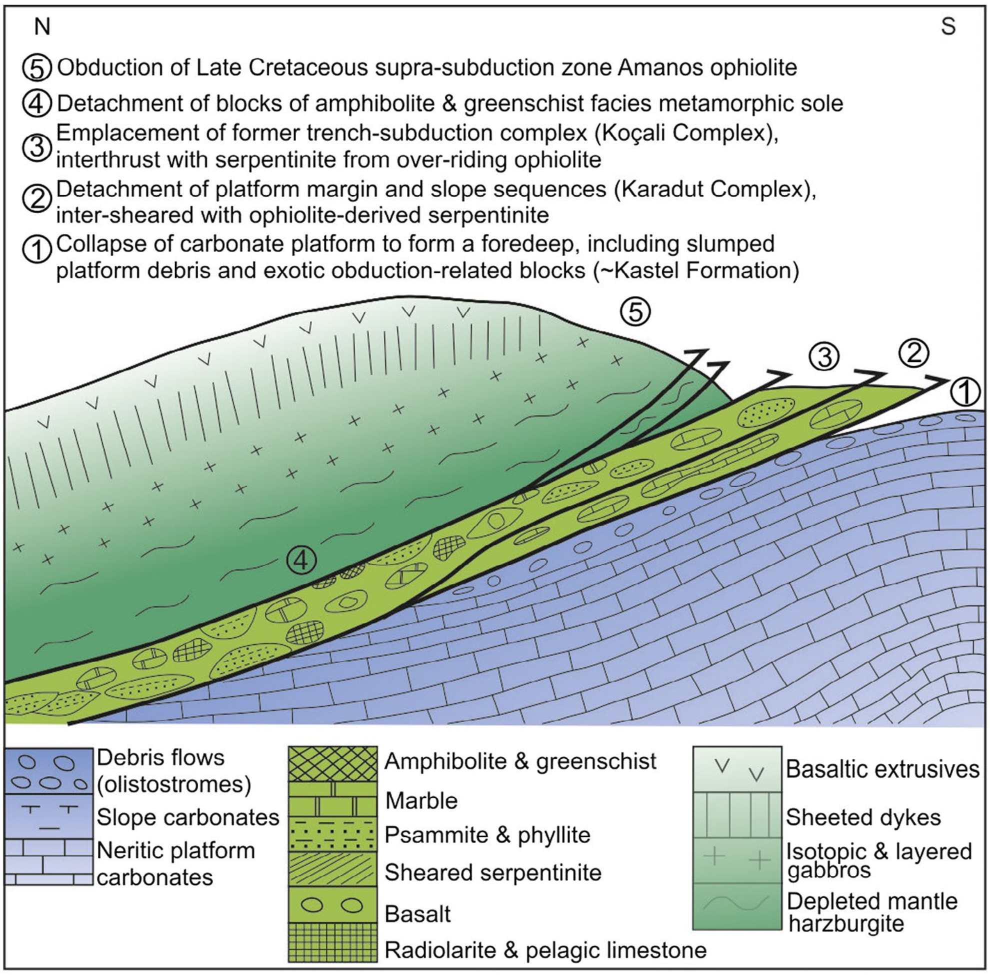

Figure 7. Interpretation of the emplacement of the Amanos ophiolite and underlying melange units onto the Arabian platform during latest Cretaceous time. A flexurally controlled foredeep developed as a result of ophiolite obduction and was then overridden by accretionary units ranging from continental margin to oceanic in origin. See text for fuller explanation.

3.4.1. Sedimentary melange (olistostrome): emplaced accretionary melange

The collapsed carbonate platform is, in places, covered by matrix-supported debris-flow deposits (equivalent to sedimentary melange or an olistostrome) that are dominated by subangular to sub-rounded blocks (up to 10 m across) of lithologies that include limestone, ribbon chert, harzburgite, gabbro and also rarely amphibolite and greenschist. For example, this heterogeneous unit was studied along a NE-SW-trending outcrop between Türkoğlu and Düziçi. The individual clasts and blocks have a brownish mudrock (shale/phyllite) matrix, which is lithologically similar to the meta-mudrock forming the highest levels of the underlying intact platform succession (Figures 5 and 6(a), (b)). A similar unit occurs between the Mesozoic carbonate platform and ophiolitic rocks in many areas of the Taurides (Yavça-type facies) (Parlak & Robertson, 2004; Robertson et al., 2012; Taslı, Özer, & Koç, 2006).

3.4.2. Heterogeneous melange; emplaced accretionary complex

This distinctive type of melange is exposed in a large area in the NE (from Türkoğlu to Şekeroba) and along the western flank of the mountain range (from Bahçe to İskenderun). It comprises blocks, up to tens of metres across, of a wide range of lithologies, within a phyllite or serpentinite matrix. The most common lithologies are recrystallized neritic limestone (marble), ribbon radiolarite and pillow basalt. Blocks of pelagic limestone, which are usually small and fragmentary, are less common; in addition, blocks of amphibolite and greenschist occur very locally (Figure 6(a)). The heterogeneous melange is commonly associated with anastomosing lenses of sheared serpentinite, typically tens to several hundred metres across and up to several kilometres long. The heterogeneous melange includes outcrops that have been mapped as both the Koçali Complex and the Karadut Complex in different parts of the Amanos Mountains (Herece, 2008; Sümengen, 2014; Yılmaz, 1984). Both complexes crop out extensively in SE Turkey where they are interpreted as an emplaced subduction-accretion complex (Koçali Complex) and the emplaced remnants of the former Arabian continental margin slope sequence (Karadut Complex) (Robertson, Boulton, et al., 2016).

3.4.3. Limestone-serpentinite broken formation/melange: emplaced continental margin fragments

The largest of the outcrops of broken formation/melange forms an NNE-SSW-trending narrow belt, ca. 110 km long and up to several kilometres wide along the eastern flank of the Amanos Mountains (from Türkoğlu to Kırıkhan) (Figure 3). However, this unit is rarely well exposed and is commonly imbricated with other units making it difficult to represent on regional-scale maps. A similar belt of rocks extends for ca. 75 km along the southeastern flank of the range (from İskenderun to Bahçe). In addition, variably disrupted sheets and blocks of Mesozoic limestone of similar origin occur locally within a matrix of sheared serpentinite (e.g. from İskenderun to Karayılan in the southwest and from Fevzipaşa to Türkoğlu in the northwest). On a regional map scale these outcrops are mostly limestone (Figure 3) although small outcrops of sheared serpentinite are found squeezed between disrupted carbonate rocks. These outcrops were previously mapped as the Jurassic-Early Cretaceous neritic carbonate platform sequence (Herece, 2008; Sümengen, 2014; Ulu, 2002b). Our observations show that this is correct in some areas, such as the central eastern flank of the range where the outcrops are contiguous with the regional carbonate platform (e.g. Fevzipaşa to Hasanbeyli). However, even in these areas the limestones are commonly sheared and disrupted suggesting that they experienced more deformation than is typical of the regional carbonate platform. Elsewhere, extending for a distance of > 20 km to the north of İskenderun (from Karayılan in the south to Dörtyol in the north), the Mesozoic and Palaeozoic sequences are separated by a major tectonic detachment, which may relate to the existence of relatively incompetent sediments (e.g. mudrocks and marls) within the Triassic rift sequence. The detachment is likely to relate to the regional emplacement of the overlying Amanos ophiolite during latest Cretaceous time.

3.4.4. Serpentinite-matrix melange: evidence of oceanic crust emplacement

The serpentinite-matrix melange provides important clues concerning the emplacement of the ophiolitic rocks (i.e. oceanic crust). Previously, this melange was included with the ophiolite in many areas (e.g. Türkoğlu, İmalı, Bahçe Düziçi, Yarpuz, İskenderun), from which it cannot easily be distinguished on a regional map scale (Figure 3). This melange is dominated by sheared, serpentinised harzburgite of ophiolitic origin, with variable inclusion of lenses and blocks of recrystallized carbonate rocks (up to hundreds of metres in size) (Figure 6(b)–(e). The dominant lithology is white marble of uncertain origin. However, there are also lenses of less recrystallized Mesozoic grey bedded limestone (e.g. around Kırıkhan). The serpentinite-matrix melange is widely developed along the western flank of the Amanos Mountains (e.g. from Andırın to İskenderun) (Figure 3).

3.4.5. Amanos ophiolite: emplaced oceanic lithosphere

The different melange units are structurally overlain by the Amanos ophiolite. In contrast to adjacent regions of SE Turkey and the Taurides only fragments of a regional-scale ophiolite are exposed within and adjacent to the Amanos Mountains. In contrast, more intact ophiolitic units occur extensively in the Karasu Valley to the east and in the Hatay area to the south (Hatay ophiolite). The outcrops in the Karasu Valley are mostly representative of the lower levels of the ophiolite pseudostratigraphy; i.e. depleted mantle harzburgite and minor gabbroic rocks. On the other hand, all levels of the ophiolite pseudostratigraphy are present in the well-documented Hatay ophiolite to the south (e.g. Aslaner, 1973; Bağcı, Parlak, & Höck, 2008; Dilek & Thy, 2009; Inwood, Morris, Anderson, & Robertson, 2009a, 2009b; Karaoğlan, Parlak, Klötzli, Thöni, & Koller, 2013; Lytwyn & Casey, 1993).

3.4.6. Regional importance of melange and ophiolite emplacement

The Amanos ophiolite and the associated melanges relate to the regional southward emplacement of Late Cretaceous oceanic crust from the Southern Neotethys onto the Arabian continental margin during latest Cretaceous time (Figure 7). The Amanos ophiolite can be correlated with similar Late Cretaceous ophiolites in the region, including the Hatay and Baer-Bassit ophiolites to the south, the Koçali ophiolite to the east (Adıyaman area) and the Troodos ophiolite to the southwest in Cyprus (Figure 1; see Robertson, 2002 and references). The inferred tectonic emplacement of the different types of melange is shown in Figure 7. The harzburgitic serpentinite was derived from the overriding ophiolite mantle sequence as a result of detachment and downward protrusion. The rare blocks of amphibolite and greenschist facies meta-igneous rocks are interpreted as fragments of the former metamorphic sole of the ophiolite which is not known to be preserved intact in the Amanos Mountains. This is because of the distinctive lithology and the location between the platform below and the ophiolitic rocks above (i.e. serpentinite melange) (Figure 5(a), (b)). A metamorphic sole is inferred to have been obducted together with the Amanos ophiolite. However, this was detached during the emplacement leaving only rare traces as blocks in the underlying melange. Comparable metamorphic sole rocks are more widely preserved associated with the Baer-Bassit ophiolite further south (e.g. Al-Riyami, Robertson, Dixon, & Xenophontos, 2002).

The radiolarites, pelagic limestone and basaltic pillow lavas of the heterogeneous melange represent fragments of an accretionary complex (Koçali Complex) related to northward subduction of the Southern Neotethys. Material was shed off the leading edge of the accretionary melange to form large-scale debris flows during the emplacement of the heterogeneous melange onto the collapsed carbonate platform (Figures 6(a), (b) and 7). The ophiolitic rocks are necessarily far-travelled from the Neotethyan spreading centre that probably formed above a subduction zone, similar to the other Late Cretaceous ophiolites in SE Turkey (e.g. Parlak, Rizaoğlu, Bağci, Karaoğlan, & Höck, 2009; Robertson, 2002). The heterogeneous melange represents emplaced fragments of the accretionary prism that formed beneath

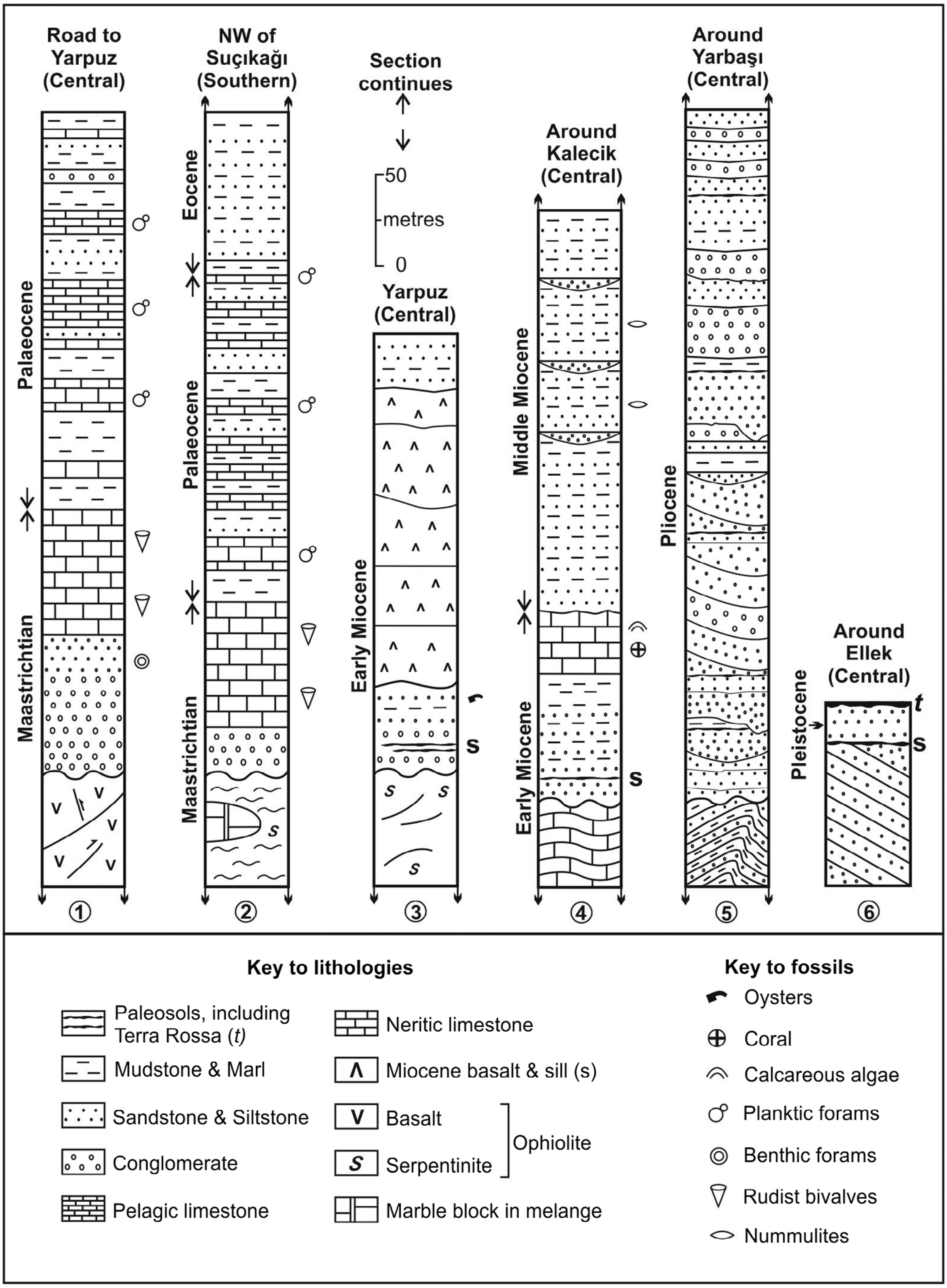

Figure 8. Summary logs showing the sedimentary setting of major unconformities in the Amanos Mountains. Each unconformity represents an important regional tectonic event. See text for explanation.

the overriding ophiolite (Koçali Complex), together with detached fragments of the former Arabian continental margin sequence (Karadut Complex).

The probable explanation of the regional low-grade metamorphism of most of the Palaeozoic-Mesozoic sequence beneath the Late Cretaceous allochthon is that the metamorphism resulted from burial beneath an originally intact slab of oceanic lithosphere, potentially > 10 kilometre-thick, which is now represented by the Amanos ophiolite. This contrasts with further south (e.g. Hatay and Baer-Bassit) where the equivalent Mesozoic platform sequence is unmetamorphosed. The Amanos platform was located relatively close to the locus of ophiolite obduction from the Southern Neotethys where the obducted lithosphere was potentially thickest, but then tapered southwards ending up with a relatively thin imbricate slice complex in the Baer-Bassit region in the far south.

3.5. Maastrichtian-Eocene sequence: resumed shelf deposition

Different units of the Upper Cretaceous allochthon are directly transgressed by clast-supported conglomerates with well-rounded clasts of ophiolitic rocks, of up to cobble-boulder size, dominantly made up of intrusive rocks (e.g. peridotite). Interbedded sandstones (up to coarse grained) are also dominantly ophiolite-derived. These basal sediments are similar to the Terbüzek Formation, which occurs directly above or adjacent to ophiolitic rocks throughout SE Turkey (Robertson, Boulton et al., 2016; Yılmaz, 1984). The sequence in the Amanos Mountain area continues with carbonate rocks which contain an *in situ* shallow-water biota, which was studied along the east-central area (between Osmaniye and Yarpuz (Figure 8, logs 1, 3). These sediments are dated as Maastrichtian in age by the presence of benthic foraminifera and rudist bivalves. Similar transgressive limestones are mapped in the south and southeast of the mountain range in the İskenderun and Kırıkhan areas (e.g. Değirmendere-Delibekirli) (Ulu, 2002b; Yiğitbaş, Yılmaz, & Genç, 1992; Yılmaz, 1984), and are similar to the Besni Formation which lies in a similar stratigraphic position throughout SE Turkey (Robertson, Boulton et al., 2016; Yılmaz, 1993). The succession then passes upwards into deepening-upwards micritic limestone, marl and mudrock (shale) containing planktic foraminifera. Interbeds of normal-graded limestone that contain reworked bioclastic carbonate are interpreted as calciturbidites. Subordinate siliciclastic sandstone interbeds are interpreted as high to low-density gravity-flow deposits (Figure 8. Log 2; Figure 9(b), (c)). This part of the sequence is broadly similar to the Germav Formation throughout SE Turkey (Robertson, Boulton et al., 2016; Yılmaz, 1984). The planktic foraminifera in the micritic limestone were dated as Late Campanian-Maastrichtian and Maastrichtian in age (see Table. 1Ⓔ, for details). The succession culminates in *Nummulites*-bearing sandstone turbidites and shales of Mid-Eocene (Lutetian) age.

In some places in the İskenderun to Kırıkhan area (Figure 3) ophiolitic harzburgite is directly transgressed by Mid-Eocene Nummulitic limestones, which can be correlated with the Midyat Group, as widely exposed throughout SE Turkey (Robertson, Boulton et al., 2016; Ulu, 2002b; Yiğitbaş et al., 1992; Yılmaz, 1984). Where observed by us near Demrek (Figure 3), the basal 1–2 m of the limestones are dark and mud-rich but lack a well-defined basal conglomerate. This overlying limestones are micritic with shaly partings and then become slightly thinner bedded and greyish-coloured upwards. Small outcrops of well-bedded, pinkish limestone, up to several tens of metres thick, occur further north.

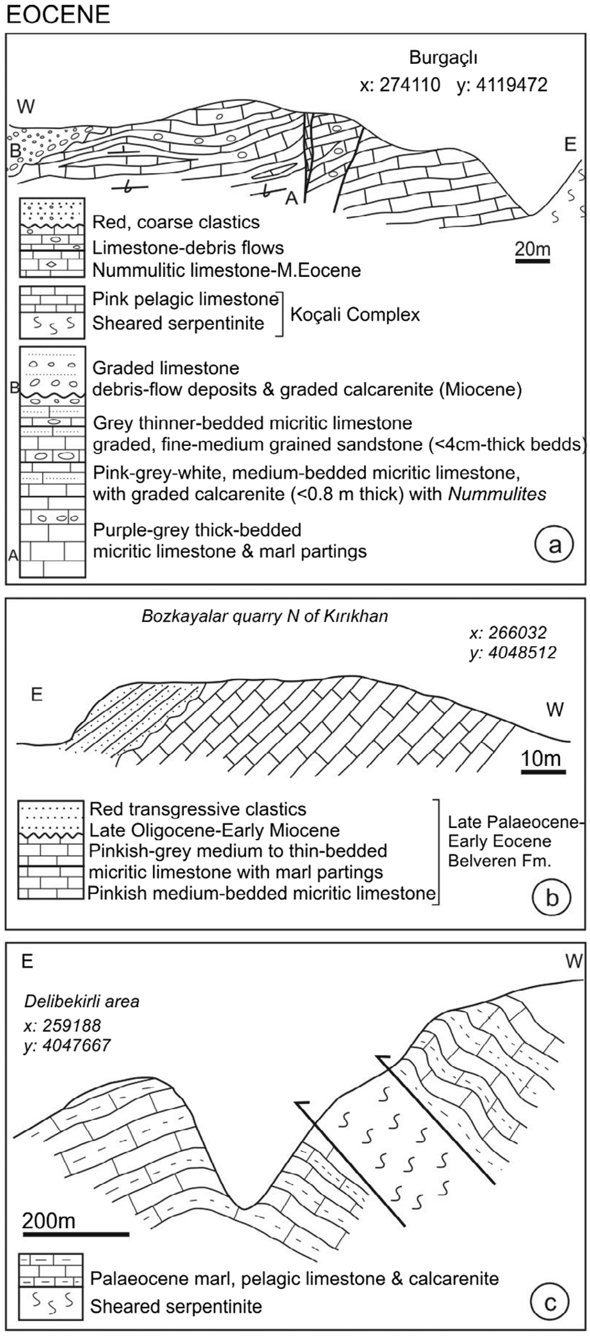

Figure 9. Local sections of sedimentary and structural features in Eocene lithologies. (a) Previously unmapped Nummulitic limestones. The limestones were confirmed to be Eocene (Middle Eocene?) in age based on planktic and benthic foraminifera (see electronic supplement). Folding observed in the Eocene sequence is absent from the transgressive Miocene sediments. Burgaçlı, central western Amanos Mountain area; (b) Eocene hemipelagic carbonates, unconformably overlain by Early Miocene clastic sediments; Bozkayalar quarry, 4.2 km N of Kırıkhan, eastern flank of southern Amanos Mountains; (c) Local interslicing of sheared serpentinite with Palaeocene-Eocene carbonates along a ca. N-S fault lineament, 4.8 km NW of Delibekirli; southern segment of Amanos Mountains.

Limestones of Eocene age are also exposed in the central Amanos region (e.g. at Kalecik, ca. 12 km SW of Bahçe (Figure 3), as indicated by benthic foraminifera (Table. 1Ⓔ). The base of the sequence there begins with grey sandstones that pass upwards into rhythmically bedded, pinkish-grey micritic limestones, rich in *Nummulites* sp. Thin interbeds (<10 cm) and partings of graded sandstone are rich in material derived from the underlying melange units (e.g. carbonate rock, chert). A small previously unmapped unit of Eocene limestone was discovered ca. 0.5 km west of Burgaçlı (ca. 10 km W of Bahçe) (Figure 9(a)). The sequence begins with medium to thick-bedded grey limestone and marl, with sparse *Nummulites* sp. and passes into regularly bedded pinkish limestone with normal-graded sandstone and bioclastic *Nummulites*-rich limestone interbeds. The local sequence ends with crudely stratified matrix-supported conglomerates that include intraformational clasts of limestone and marl, of similar lithologies to the underlying sediments. This uppermost interval is interpreted as a mass-flow deposit related to tectonic disturbance and gravity reworking of the subjacent sequence.

After the emplacement of the melanges and ophiolitic rocks the Amanos Mountain region was subaerially exposed and deeply eroded. The main evidence for deep erosion is that the overlying conglomerates were mainly derived from intrusive ophiolitic rocks (e.g. peridotites). This contrasts, for example, with the Hatay area further south where the entire ophiolitic pseudostratigraphy is preserved beneath transgressive Late Cretaceous sediments (Boulton, 2009; Boulton & Robertson, 2007).

The southern part of the Amanos region is known to have been transgressed by a shallow sea during the Maastrichtian. During the Palaeocene-Early Eocene the sea became sufficiently deep (up to several hundred metres) to allow the accumulation of fine-grained hemipelagic carbonate. Interspersed bioclastic gravity-flow deposits (mostly calciturbidites) accumulated in shallow-water marginal areas. The upper part of the succession, both in the south and further north (at Burgaçlı), shows abundant evidence of tectonic instability, as indicated by the presence of debris-flow deposits. In the south, the sequence culminated in deposition of Mid-Eocene sand-rich gravity-flow deposits (Boulton,

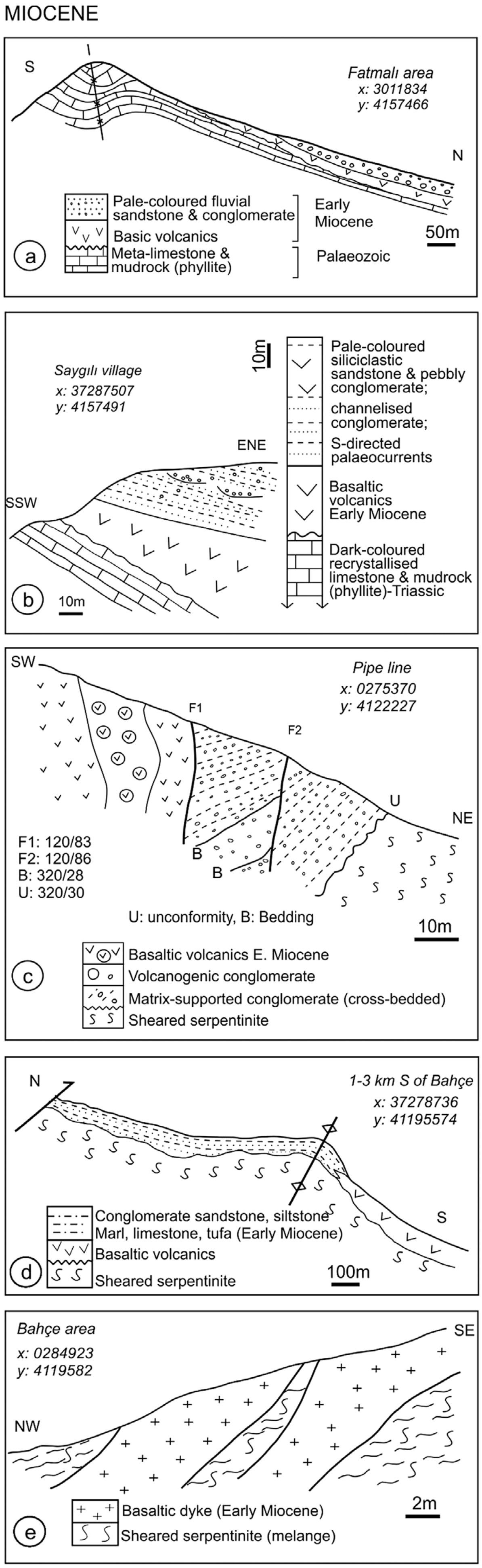

Figure 10. Local cross-sections of Miocene sedimentary and structural features (arranged from north to south). (a) Mesozoic meta-carbonate and minor phyllite, transgressively overlain by Early Miocene coarse clastic sediments and intercalated basaltic flows that are open-folded along ca. N-S axes (Late Miocene?); Fatmalı, northern Amanos Mountains; (b) Dark, recrystallized limestone (Triassic), unconformably overlain by Early Miocene basalt and non-marine clastic sediments; Saygılı (7.4 km SW of Yenicekale), NW Amanos Mountain area; (c) Unconformity between ophiolitic serpentinite and overlying Early Miocene non-marine clastic sediments and fragmental basaltic rocks, cut by high-angle strike-slip faults (Plio-Quaternary; 5.5 km S of Düziçi; (d) Sheared serpentinite overlain by Early Miocene clastic sediments and basaltic rocks that are open-folded and overthrust (owing to Late Miocene deformation?); 8 km SW of Bahçe; (e) Serpentinite melange intruded by basaltic dykes of inferred Early Miocene age; main road cutting near Bahçe.

2009), again pointing to tectonic instability. In contrast, areas further north remained emergent at least until the Eocene, and it not known whether Eocene sediments were ever deposited in the northern Amanos Mountain area.

3.6. Early Miocene succession: destabilisation of the platform and associated volcanism

The ophiolite, the melange and, where present, the Maastrichtian to Eocene sequence are unconformably covered by transgressive sediments of Early Miocene age. In the north and west, basal, unfossiliferous, non-marine clastic and carbonate sediments are overlain by Early Miocene limestones with shallow-marine fauna (Karaisalı Formation) (Kozlu, 1982). Locally in the south, near-basal sediments have been confirmed as Early Miocene based on planktic foraminifera and ostracods (Boulton, 2009).

A complete Early Miocene sequence is exposed northwest of the mountain flank (e.g. 7.4 km SW of Yenicekale). This begins with red non-marine ophiolite-derived clastic sediments and terrestrial paleosols and passes upwards into Early Miocene shallow-marine fossiliferous limestones (Figure 10(b)). Along the north and northwestern flanks of the range, in contrast, Mesozoic metacarbonate rocks are directly overlain by subaerially erupted basalts (up to ca. 60 m thick), typically with a low-angle (<20°) discordance between them (e.g. from near Önsen to Saygılı).

The basalts are overlain by, and locally interbedded with, buff-coloured sandstones and conglomerates (Figure 10(a) and (b)). The clastic material is well-rounded and well sorted. Well-developed cross-bedding indicates northward fluvial palaeoflow, as observed around Yenicekale.

Further south, the Mesozoic allochthonous rocks (or where present, the Eocene limestones) are variably overlain by non-marine sediments and volcanic rocks. These lithologies are exposed within a broad embayment of the central-western flank of the Amanos Mountains that extends for ca. 15 km NE-SW, from Kalecik and Hasanbeyli in the north to Yarpuz in the south. The succession in this area locally begins with red fluvial conglomerates, up to several tens of metres thick (Figure 8, log 3, 4).

Measurement of closely spaced logs shows that the conglomerates occur in depressions (tens to several hundred metres wide), effectively broad channels eroded into the substratum. The clasts in these conglomerates are mostly crystalline carbonate rocks, ophiolitic rocks and also unmetamorphosed basalt, suggesting that the erosion took place during or soon after eruption. The succession in the Bahçe area passes upwards into lithologically varied grey-brown lenticular, channelized fluvial sandstones and conglomerates, which locally range from clast supported to matrix supported. The alluvial facies are interbedded with laterally discontinuous basaltic flows, up to tens of metres thick, together with minor intrusions (Figure 10(c) and (d)). Some of the fluvial conglomerates contain well-rounded clasts of basalt of similar composition to the intact flows and dykes. The adjacent 'basement' rocks in this area are locally cut by basaltic dykes or sills (Figure 10(e)). Basaltic sills that occur within Early Miocene sediments elsewhere (Yarpuz area) are assumed to be co-magmatic with the basaltic extrusives. Cross-cutting dykes of similar-composition basaltic rocks occur in several other areas where no Miocene sediments are exposed (e.g. S of Önsen in the NE area). Small accumulations of lacustrine carbonate and vegetative tufa are also present locally. To the southwest of Bahçe (between Hasanbeyli and Yarpuz), mixed sequences of grey-brown conglomerate, lenticular sandstones and shales contain marine macrofossils, suggesting a lateral passage from non-marine to marine conditions in this direction.

In the southwest of the Amanos Mountains (e.g. locally near Belen), the Eocene limestones are unconformably overlain by Early Miocene shallow-marine facies, which include neritic shelly fauna. The uppermost exposed Eocene limestones in the Belen area are fissured and infiltrated by coarse sandstone and pebblestone. An overlying basal conglomerate (less than several metres thick) is made up of well-rounded but poorly sorted clasts. The clasts are dominated by grey chert and fine-grained limestone that were derived from the underlying Eocene succession, together with occasional ophiolitic rock clasts (e.g. gabbro). The succession passes upwards into a thinning and fining-upward succession of shallow-marine siliciclastic sediments (e.g. Boulton & Robertson, 2007). More typically in the Belen area, Early Miocene marine deposits are restricted to a very thin (5 m) horizon, whereas this time interval is dominated by continental alluvial fan/fan delta facies (Kici Formation) (Boulton, 2009).

Further east, along the margin of the Karasu Valley, near Kırıkhan, ophiolitic harzburgite or Eocene limestone (in different areas) are overlain by reddish paleosols, caliche and conglomerate above a low-angle unconformity (<15°). The succession continues with well-sorted, lenticular sandstones, made up of individual depositional units (up to ca. 8 m thick), and interspersed with shell-rich beds and mudrocks of Early Miocene age.

Following the transgressive shallow-marine deposition during the Paleogene, the whole of the Amanos Mountain region became emergent during the Late Eocene-Oligocene. In the northern part of the region, Early Miocene sedimentation was initially non-marine, whereas shallow-marine sediments accumulated directly on Eocene 'basement' in the south and east (Boulton, 2009; Boulton & Robertson, 2007; Boulton, Robertson, & Ünlügenç, 2006). Although an Early Miocene age for the non-marine sediments is assumed, a Late Oligocene age is not precluded, especially for the well-oxidised reddish-coloured basal conglomerates because Oligocene facies elsewhere are similar (e.g. in the Ecemiş corridor (Jaffey & Robertson, 2005)). The composition of the basal clastic sediments is consistent with relatively local derivation from the Late Cretaceous allochthon or the Paleogene succession in the Amanos Mountain area. Locally (e.g. near Yarpuz; Figure 3), Miocene sediments are transgressive on the Mesozoic autochthonous platform carbonates (Ulu, 2002b) showing that the Late Cretaceous allochthon was eroded prior to this time in some areas. However, the level of erosion had yet to reach the deeper-level Palaeozoic rocks.

In the northwest, Early Miocene deposition was accompanied by basaltic magmatism in an inferred extensional setting. The overall pattern of sedimentation and volcanism records tectonic destabilisation of the Arabian platform. The likely explanation is flexural loading related to the initial stages of emplacement of the Tauride allochthon, as recently documented in SE Turkey (e.g. Adıyaman area) (Robertson, Boulton, et al., 2016).

3.7. Mid-Late Miocene sequence: foreland basin development

Contrasting successions characterise the western versus the eastern flank of the Amanos Mountains. Along the western and northern periphery of the Amanos Mountains the Early Miocene carbonate platform broke up and subsided to form a Langhian-Serravallian-aged (Kozlu, 1987; Yılmaz, Gürpınar, & Yiğitbaş, 1988; Gül, Gürbüz, & Cronin, 2011; Robertson, Ünlügenç, İnan, & Taşlı, 2004) deep-marine turbiditic foreland basin, in which siliciclastic sediments were sourced from the Tauride allochthon. These sediments form part of the much larger K. Maraş Basin which borders the Amanos Mountains to the north and northeast. For example, in the far northwest of the area (just west of Yenicekale), shallow-marine limestones culminate in spectacular limestone-derived debris-flow units and slumps. These 'catastrophic' facies are then depositionally overlain by siliciclastic gravity-flow deposits, hundreds of metres thick (e.g. Yılmaz et al., 1988; Yılmaz & Gürer, 1996). This deep-sea sequence, dominantly turbidites, is interpreted as a foreland basin that formed in response to flexural loading by the overthrusting Tauride active continental margin. The basin was terminated by overthrusting by the Tauride allochthon (see below) as the Southern Neotethys sutured.

In contrast, in the southeastern area, specifically around Kırıkhan, the Early Miocene shallow-marine deltaic deposits pass depositionally upwards into relatively thin-bedded quartz and mica-rich turbidites for which the Palaeozoic basement to the north of K. Maraş is a possible source (Boulton, 2009; Boulton & Robertson, 2007); however, there is no evidence of overthrusting by Tauride units. Also, there is no evidence of major uplift and deep erosion of the Amanos Mountain Palaeozoic stratigraphy until the Pliocene.

In addition, the Middle Miocene of the adjacent Hatay area is characterised by peritidal carbonates (Sofular Formation), together with contemporaneous, small patch reefs (Kepez Formation), as exposed near Serinyol and Kırıkhan (Boulton & Robertson, 2007; Boulton et al., 2006). This area was so far from the overthrust Tauride allochthon that it was less influenced by crustal flexure during Early-Middle Miocene time.

3.8. Pliocene sequence: syn-uplift sedimentation

Pliocene deposits are extensive to the west of the central Amanos Mountains (SW of Düziçi) and southwest of Hatay (Samandağ area). In addition, Pliocene deposits are mapped to the south of the EATF, as exposed to the northwest of K. Maras (Gölbaşı-Pazarcık area) (Ulu, 2002b). Until now accurate dating of these deposits has not been achieved and an Early Pleistocene age for some of these coarse clastic deposits cannot be excluded.

To the west of the central Amanos Mountains, the Mid-Miocene foreland basin sequence was folded and faulted related to overthrusting by the Tauride allochthon, which in this area is dominated by an Eocene-Oligocene assemblage (Figure 3; see below). These rocks were then unconformably overlain by reddish coloured, non-marine conglomerates (up to several hundred metres thick) of inferred Pliocene age-Early Pleistocene(?) (Figure 8, log 5). These sediments dip regularly at angles of up to ca. 30°. The conglomerates are thick-bedded, or massive and range from matrix-supported, to clast-supported within individual depositional units (Figure 11(a)). The clasts are mostly sub-rounded (up to ca. 60 cm in size). Individual depositional units vary from some that are dominated by Mesozoic limestone to others that are mostly made up of quartzose sandstone of similar lithology to the Palaeozoic rocks of the Amanos Mountains. Clast imbrication ranges from absent in the most matrix-supported conglomerates to moderately well-developed in the more clast-supported conglomerates (Figure 11(b)). Clast imbrication direction ranges from nearly constant within some outcrops, to variable within others. In the centre of the main outcrop, relatively close to the range front, palaeoflow is towards the west and southwest (e.g. near Şekerdere, 9.6 km SW of Burgaçlı); further west, away from the range (e.g. near Toprakkale), palaeoflow is more towards the south. Some of the thicker conglomeratic units (individually up to ca. 5 m thick) are laterally continuous and planar, whereas some of the thinner and generally finer units are channelized downwards into fluvial sandstone, paleosols (with or without caliche) or lacustrine deposits. The uppermost parts of the succession are characterised by thinner-bedded, finer conglomeratic units, interbedded with buff-coloured sandstones, reddish paleosols

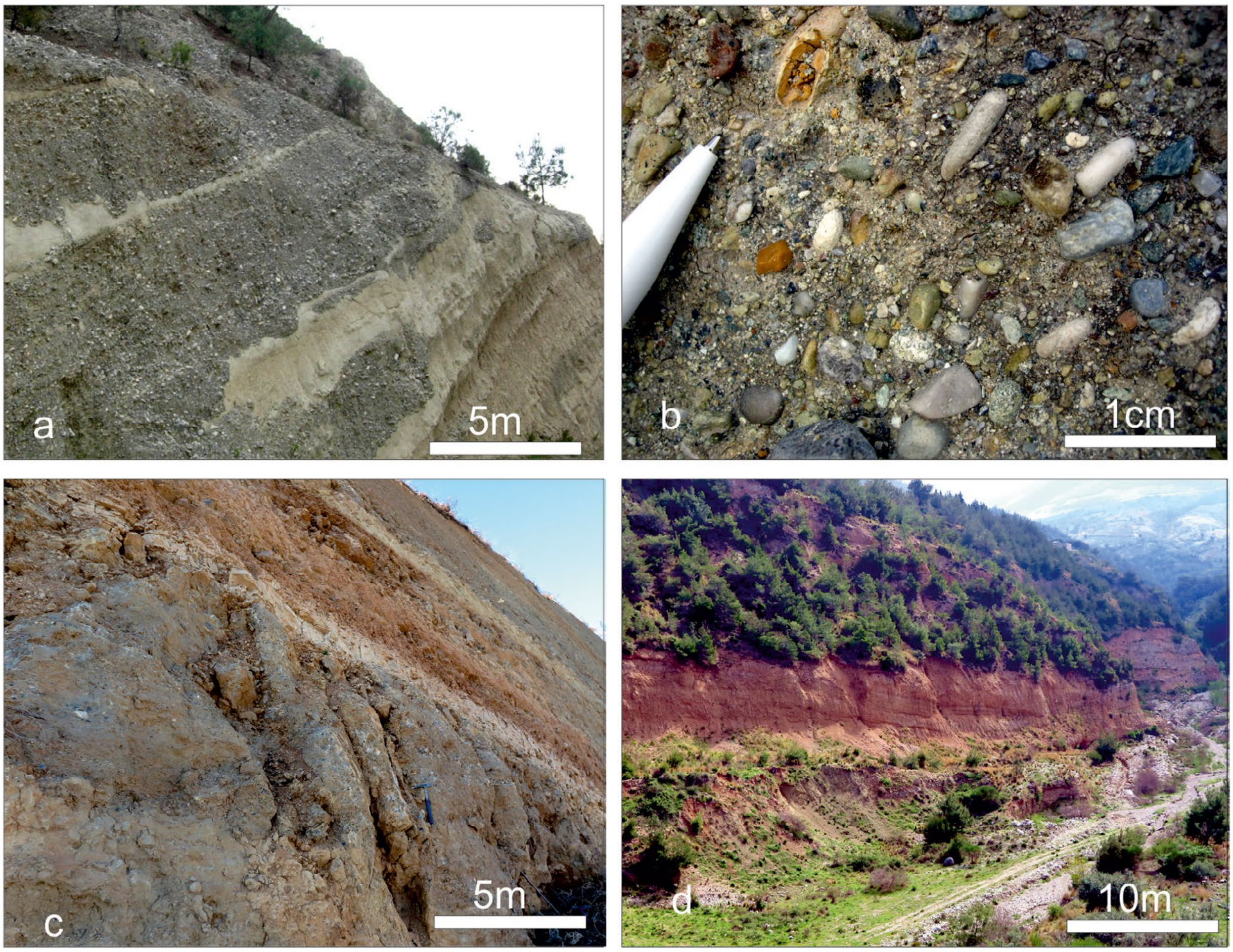

Figure 11. Field photographs showing sedimentary features of the Pliocene and Quaternary deposits. (a) Pliocene deltaic sediments, Toprakkale; (b) Clast imbrication indicating southward palaeoflow, Toprakkale; (c) Alluvial fan deposits intercalated with lacustrine facies (exposed on a synclinal limb), Fevzipaşa; (d) Tilted (ca. 15°) Quaternary fan deposits, İskenderun area.

and white lacustrine marls (e.g. near Toprakkale). In the south, gently dipping Pliocene sediments are covered by subhorizontal Quaternary basalt.

The Pliocene-Early Pleistocene(?) sediments provide evidence of deep erosion and large-scale runoff of coarse clastic debris from various different levels of the Amanos Mountain stratigraphy, down to and including the Palaeozoic succession. Talus was shed westwards and southwestwards along the western flank of the range, but generally southwards in the most westerly outcrop (near Toprakkale). The detritus was initially transported away from the range front in this area, but was then carried southwards into the Gulf of İskenderun. The conglomerates were dominantly laid down within high-energy braided streams. Ephemeral shallow lakes waxed and waned, interspersed with periods of paleosol and caliche development.

Sediments of inferred Pliocene-Pleistocene(?) age that are locally exposed along the eastern flank of the range provide evidence of strong uplift and erosion, corresponding to the present Amanos Mountains. The eastern flank is generally covered by Pleistocene-Recent material. However, a small, previously unrecognised outcrop of Pliocene-Early Pleistocene(?) alluvial fan sediments (>75 m thick) is exposed in the centre of the area (Fevzipaşa area) beneath well-dated subhorizontal Quaternary basalt (e.g. Çapan, Vidal, & Cantagrel, 1987; Rojay, Heimann, & Toprak, 2001). Buff-coloured conglomerates and yellow sandstones there are intercalated with silty and fine sand-rich lacustrine facies and also include calcrete nodules (Figure 11(c)). The conglomerates are thick bedded, to massive, range from matrix supported to clast supported, and are dominated by sub-rounded clasts (up to ca. 50 cm in size). The sequence is open-folded, parallel to the mountain range and dips at angles of up to ca. 25° NNE, towards the range,

3.9. Pleistocene deposits: erosion, deposition and syn-sedimentary faulting

The eastern flank of the range, as exposed along the western margin of the Karasu Valley, is characterised by a series of alluvial fans, individually ca. 4–6 km wide and 3–4 km across (Figure 12). The fans are fed by numerous closely spaced (ca. 1–3 km), up to 10 km-long stream-courses that extend up to the highest levels of the mountain range. In the Karasu Valley, boreholes indicate that Pleistocene sediments >200 m thick were deposited, increasing to ca. 360 m towards the Amik Plain (Rojay et al., 2001). Very coarse, poorly sorted conglomerates predominate, mostly of inferred Palaeozoic lithologies (e.g. quartzite).

In some areas (e.g. Hassa and Islahiye areas), the alluvial fans are partially covered by, or interbedded with, Quaternary basalts. These basalts, which are dated as 0.2–2 Ma (Çapan et al., 1987; Rojay et al., 2001; Seyrek et al., 2007; Yurtmen, Guillou, Westaway, Rowbotham, & Tatar, 2002), are locally cut by both strike-slip and normal faults.

The western flank of the Amanos Mountains is free of Pleistocene conglomeratic deposits in the north (e.g. Osmaniye to Düziçi), owing to fluvial bypassing towards the coastal plain and the Gulf of İskenderun. Further south (from Osmaniye to İskenderun), alluvial fans (rich in paleosols) are developed near the mouths of very deeply incised stream courses (e.g. Erzin, Dörtyol, Karayılan). However, the size and distribution of the deposits are largely concealed by the Gulf of İskenderun in this area. In the Ceyhan River, specifically, seven main fluvial terrace levels are present, up to 230 m above the river, as observed in the Duziçi area (Seyrek et al., 2008).

One of the lower terrace levels of a Ceyhan River tributary is backed by a sloping erosional surface (e.g. in the Bahçe area), which reaches nearly as far as the crest of the range (a saddle of relatively low relief in this area). As a whole, the alluvial fans are tilted eastwards (ca. 10–15°) along the western flank of the range (from Düziçi to İskenderun) (Figure 11(d)). In places around the western flank of the range (e.g. Bahçe area), later-Pleistocene terrace deposits developed within earlier-Pleistocene alluvium.

3.10. Outline geomorphological development

The topography of the mountain range has resulted in an asymmetrical drainage pattern with relatively long, moderately inclined erosional profiles to the west of the drainage divide vs. shorter and steeper profiles to the east of the drainage divide (Figure 12). This asymmetrical morphology mainly relates to the Neogene-Recent structuration of the Amanos Range, as discussed below but is also strongly influenced by differential erosion of lithologies of contrasting rheology (see Electronic Supplement Figure 6).

The Palaeozoic-Mesozoic core of the mountains is transected by the Ceyhan river gorge with a highly immature geomorphology. This is flanked by some of the highest peaks in the Amanos Mountains, with a relief of up to 2000 m. The sinuous trend of the river valley reflects antecedent drainage. In places, downcutting has truncated pre-existing drainage courses to form hanging valleys, which later became the sites of, for example tufa deposition. In general, the Amanos Mountain geomorphology has been strongly influenced by lithology, with the resistant metamorphic rocks retaining a rugged topography in contrast to the relatively smooth topography developed on the Miocene sediments. Erosion has also resulted in the basal thrust of the Late Cretaceous allochthon, a horizon of nearly uniform erosional resistance, developing into a smooth, gently westward-sloping surface (e.g. Düziçi area).

4. Structural development

In preceding discussion, we have shown how the lithostratigraphy and sedimentology shed light on the geological evolution of the Amanos Mountains. Below, we integrate supporting structural geological information which becomes meaningful in the context of the geological development. In particular, we highlight the large-scale structure of the Amanos Mountains. The structures are described below according to their style of deformation and the age of the units in which they occur. The following main types of structure were observed and analysed: bedding, schistosity, lineations, fold axial planes, trend and plunge of fold axes, fault orientation and trend/ plunge of fault planes slickensides (including sense of movement, where possible). Stereoplots are presented for bedding (168), schistosity (47), fold axes (88) and fault orientation (240) (Figure 13(a)(d)). The data which were mostly collected along accessible sections and transects: the Yenifarsak and Orcan valleys, the Ceyhan Valley, and the Türkoğlu-Bahçe corridor. The results are summarised in Table 2Ⓔ and fully listed in the electronic supplement. The stereoplot analysis utilised the FaultKin program (V 6.6.3, Allmendinger, Cardozo, & Fisher, 2012; Marrett & Allmendinger, 1990). In addition, six representative cross sections of the Amanos Mountains were constructed to help identify large-scale structural features (Figure 14(a)(f)). Photographs of key structural features are shown in the Electronic Supplement (Figures 4 and 5).

4.1. Structures affecting Palaeozoic and Mesozoic sequences

Similar styles of deformation affect the Palaeozoic and Mesozoic sequences up to, but excluding, the Late Cretaceous melange/broken formation and the ophiolite.

Bedding-parallel cleavage is widely developed, whereas bedding-oblique cleavage related to folding is rare (Figure 13(a), (c)). Local occurrences of cleavage at a lower angle than bedding are indicative of recumbent folding (e.g. Nurdağı, central west area). Intense N-S trending and east-verging folding tend to be concentrated along elongate ca. N-S high-strain zones. Good examples occur close to the Ceyhan River in the north, further south in the Türkoğlu-Bahçe area, along the eastern margin of the mountain range from Türkoğlu to Hassa, and also in the Belen area, SE of İskenderun (Figure 14(b)–(d), (f)). Most of the folds are of brittle, cylindrical type (Figure 15(a)). Fold styles ranges from upright, to inclined, to recumbent and include rare refolded folds, as

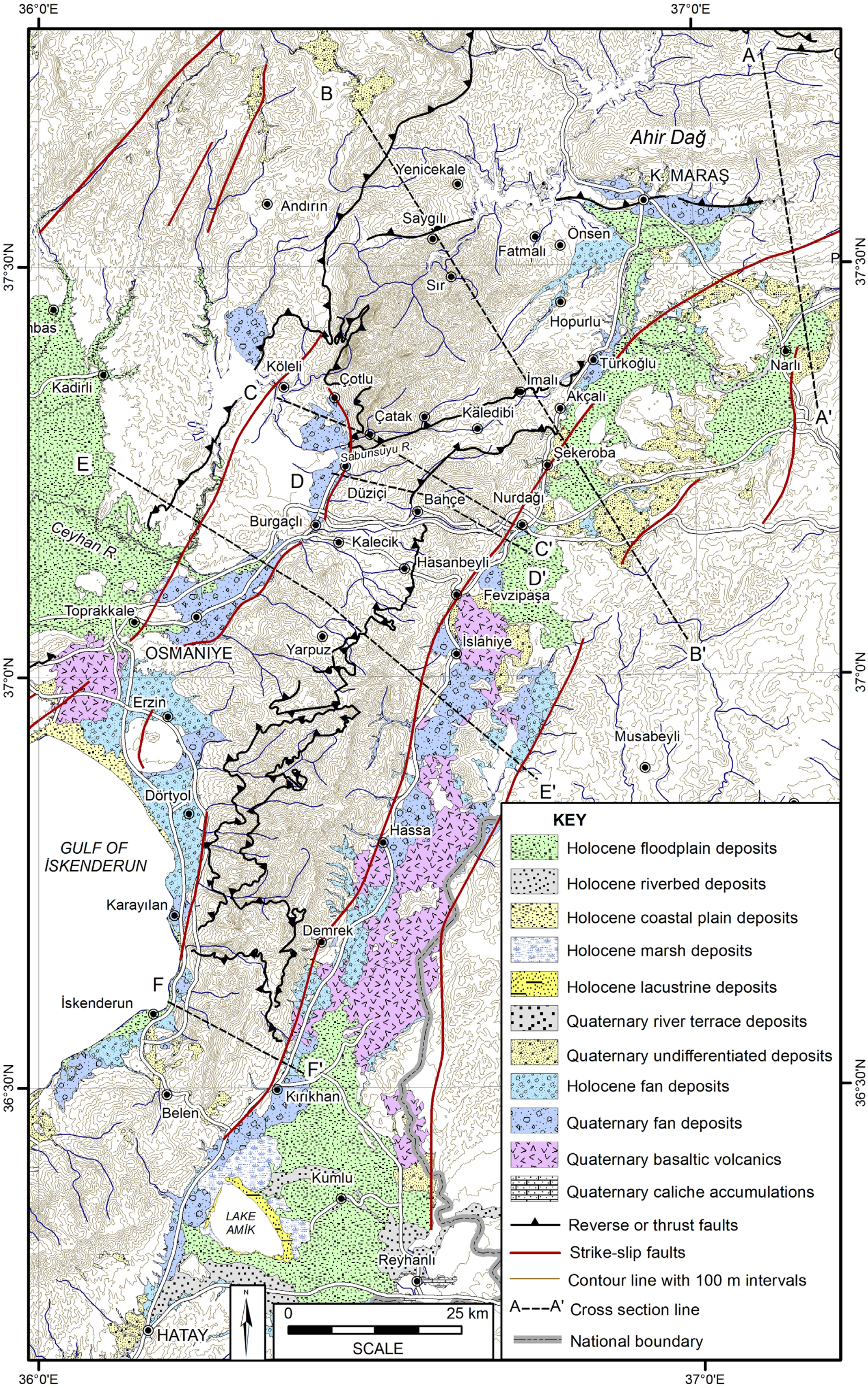

Figure 12. Quaternary-Holocene geology showing neotectonic faults superimposed on a contoured map of the Amanos Mountains (also showing the main roads, settlements and the lines of section, as in Figure 3). The Quaternary-Holocene geology and strike-slip faults are from Duman and Emre (2013); reverse faults are from Ulu (2002b), Duman and Emre (2013) and this study. The contour data are from 90-m resolution Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) data (Jarvis, Reuter, Nelson, & Guevara, 2008). Source: Authors

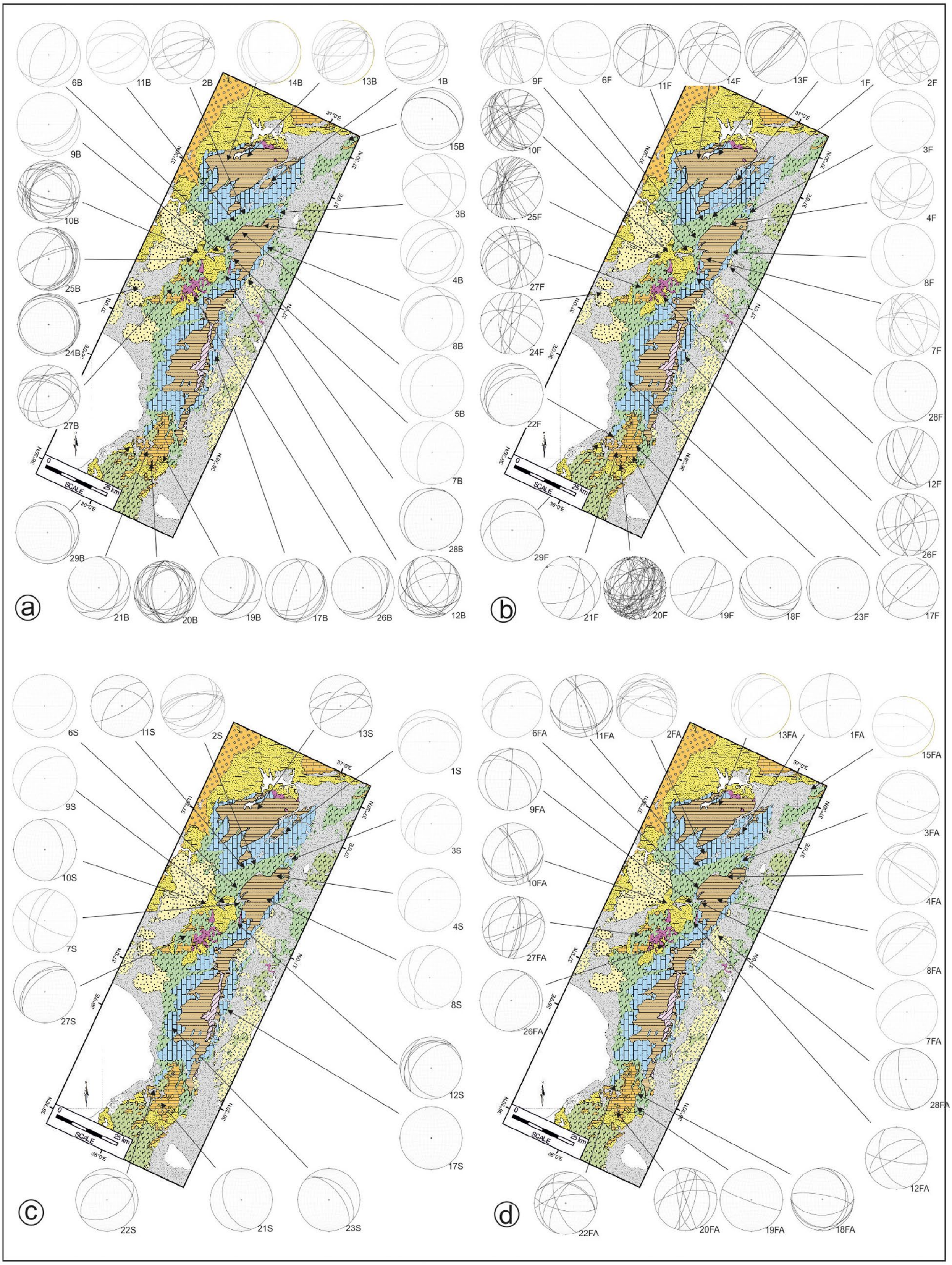

Figure 13. Stereoplots of bedding, schistosity, fold axes and fault planes that were measured in the study region. Abbreviations; B, bedding; F, fault; S, schistosity; FA, fold axis. Numbers indicates observation locations (see he supplementary electronic material in Table 2Ⓔ for the locations of observations).

seen in the Mesozoic sequence along the western margin of Nurdağı (Figures 14(c), (d) and 15(b)).

The intensity of deformation increases upwards, towards the over-riding allochthon. The highest exposed levels of the autochthonous sequence (several tens of metres thick) commonly exhibit intense shearing and ductile folding (e.g. Düziçi and Bahçe areas). A well-developed penetrative stretching lineation, orientated

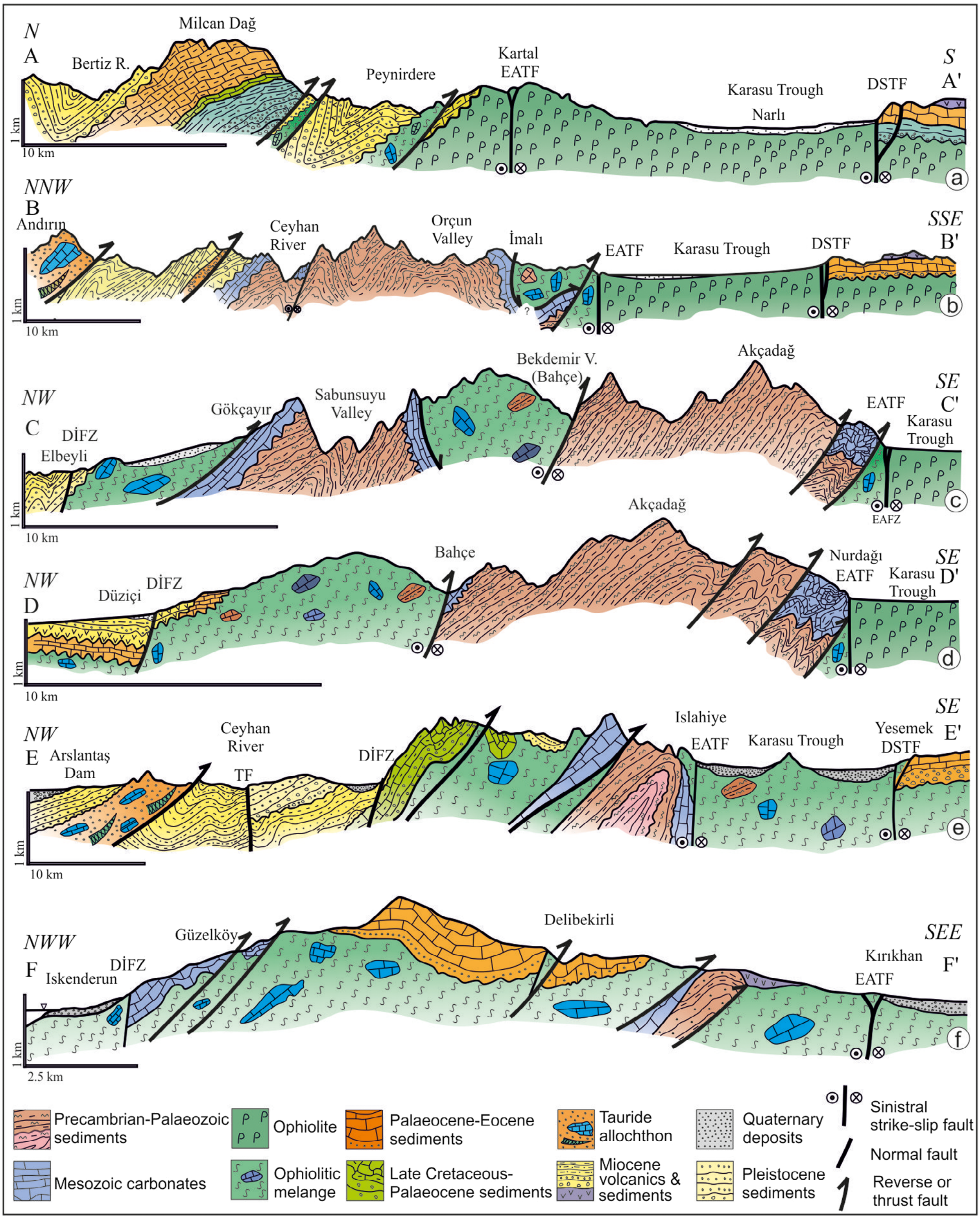

Figure 14. Simplified cross sections of the Amanos Mountains and related units. (a) N-S from Milcan Dağ to Pazarcık area; (b) NW-SE from Andırın to Türkoğlu; (c) Middle section from Düziçi area to Nurdağı; (d) NW-SE from Burgaçlı to Nurdağı; (e) South of Kadirli to Islahiye-Yesemek; (f) İskenderun to Kırıkhan. See Figures 3 and 12 for locations. Abbreviations: EATF, East Anatolian Transform Fault; DSTF, Dead Sea Transform Fault, DİFZ, Düziçi-İskenderun Fault Zone.

ca. N-S, occurs in several areas (e.g. near Çotlu, close to the Ceyhan River).

An exceptional high-angle, NE-SW-trending fault traverses the central northern Amanos Mountains, over ca. 13 km (from Kaledibi to Bahçe) (in the Bekdemir Valley in Figure 14(c); and at the Bahçe in the centre in the Figure 14(d)). To the west, the fault is bounded by ophiolite-related melange, whereas to the east it transects the Palaeozoic-Mesozoic sequence which dips to the south-west at right angles to the fault zone. The stratigraphical relations (i.e. northwards younging at right angles to the fault trend) confirm the presence of a large-scale fault,

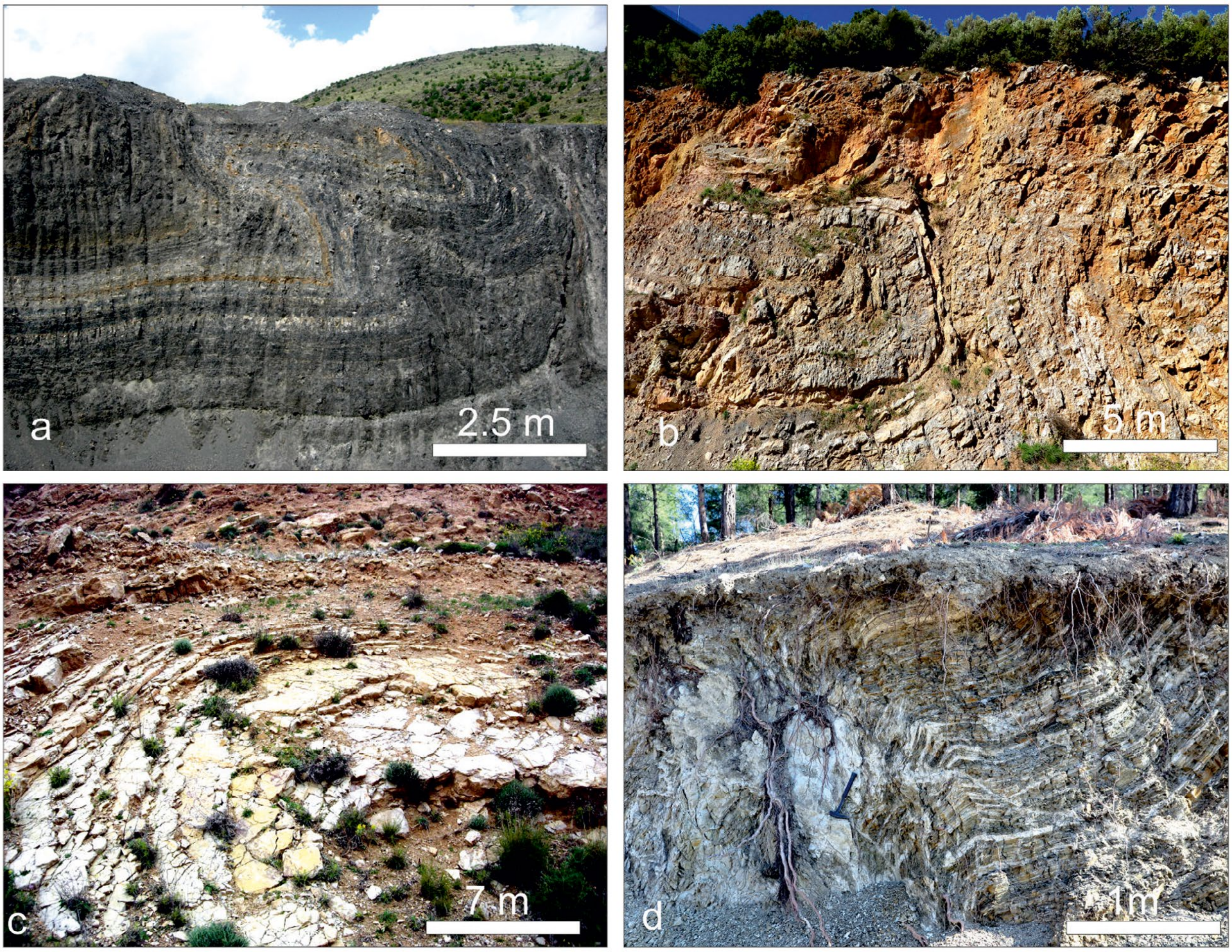

Figure 15. Field photographs of outcrop-scale structural features in the Amanos Mountains. (a) S-shaped cylindrical fold in Late Palaeozoic black phyllite-quartzose sandstone; northern flank of a major SE -vergent structure (Late Miocene-aged structure?), Hopurlu, Sır area, northern Amanos Mountains; (b) SE-verging recumbent folds in Mesozoic limestone, road section highway viaduct, ca. 2.3.km W of Nurdağı (Late Miocene?); (c) S -verging cylindrical fold in Palaeocene limestone, road cutting ca. 2 km SE of Belen; (d) Asymmetrical fold in Miocene sandstone, mudstone, road cutting ca. 2.5 km SE of Belen (Late Miocene deformation?).

in which the throw increases northwards. Unfortunately, kinematic indicators could not be observed along or adjacent to this major high-angle fault. However, the apparent termination of the fault both to the north and south appears to preclude an origin as a throughgoing fault, for example a strike-slip fault. This regional-scale high-angle fault could reflect decreasing stress southwards along the axis of the mountain range in a setting of regional thrusting and transpression (see below). In this case the fault offset was greatest in the north, closest to the zone of Mid-Late Miocene overthrusting and decreased southwards away from the zone of maximum compression/transpression.

The Palaeozoic-Mesozoic sequences, together with the overlying melange units (exposed in the Türkoğlu-Bahçe corridor, Türkoğlu-Nurdağı and Nurdağı-Kırıkhan areas) are folded into a mountain-scale anticlinorium of which the overall fold axis direction changes from NE-SW to N-S (Figure 14(b)–(e)), from north to south. In places (e.g. Şekeroba, Nurdağı), outcrop-scale folds that are related to this structure have been reactivated by SE and E-vergent reverse faults (Figure 14(c) and (d)).

4.2. Structures affecting melange/broken formation and ophiolite

The heterogeneous melange (Koçali Complex) shows a similar style of deformation to that within the uppermost levels of the underlying autochthon, with a well-developed schistosity and ductile-style folding. The phyllitic matrix exhibits bedding-parallel cleavage and small-scale isoclinal folds. Similarly, the intercalated serpentinite matrix, where present, is highly sheared and folded, in places forming serpentinite mylonite (e.g. Kırıkhan area). Some blocks retain relict magmatic textures (e.g. harzburgite). Blocks of other lithologies including radiolarite and bedded limestone commonly show intense layer-parallel extension, creating classic phacoidal fabrics (e.g. E of İskenderun). In places, the schistosity in both the phyllitic and serpentinite matrix is folded on scales ranging from a few centimetres to tens of metres, indicative of polyphase deformation (Figure 16(b) and (c)). Isoclinal folding was observed within a block of Late Cretaceous fossiliferous limestone near Akçali, NE of Türkoğlu. Serpentinite close to the contact with the underlying platform sequence is intensely sheared, crenulated and folded. In addition, the serpentinite-marble melange, where present, shows evidence of intense shearing (e.g. Berke dam, NW of Köleli; northwestern flank). In contrast, peridotite of the over-riding ophiolite thrust sheet is relatively undeformed and unmetamorphosed (e.g. in the Karasu Valley).

In some areas, the basal thrust and the units exposed above and below this structure are folded together. For example, along a NE-S-trending zone in the northwest, the Mesozoic platform sequence and the melange units are deformed into kilometre-scale, SE-facing, inclined folds over a distance of ca. 20 km (SW of Türkoğlu; Figures 14(b), (c) and 16(c)). The large-scale thrust structure is locally offset by transverse faults, with lateral displacements in excess of several hundred metres. In this area, limestone was detached from its parent platform and accreted to the base of the over-riding allochthon in the form of broken formation or melange during emplacement (Figure 14(e) and (f)).

The intensity of the large-scale folding increases southwestwards, passing into a ca. 20 km-long, NE-SW-trending overturned fold, or nappe (NE of Düziçi) (Figure 14(c)). A major reverse fault separates Palaeozoic metaclastic rocks from sheared serpentine, as exposed along the southern border of the Türkoğlu-Bahçe corridor. This fault is orientated parallel to the regional-scale fold in the NE (near Türkoğlu), but then swings southwards towards Bahçe and Kırıkhan (Figure 17(a)). East of İskenderun, melange (which includes up to hundreds of metre-sized inclusions of Mesozoic limestone), is deformed into trains of east-verging folds, of up to kilometre scale (Figure 14(f)).

4.3. Structures affecting Eocene sequences

In some areas, Eocene marine limestones are relatively undeformed and only gently inclined, as seen in much of the southern Amanos Mountains, for example along the southeastern margin of the range (e.g. between Hassa and Kırıkhan) and in the central-west mountain area (near Kalecik). Elsewhere, the Eocene limestones are more steeply dipping and deformed. Deformation,

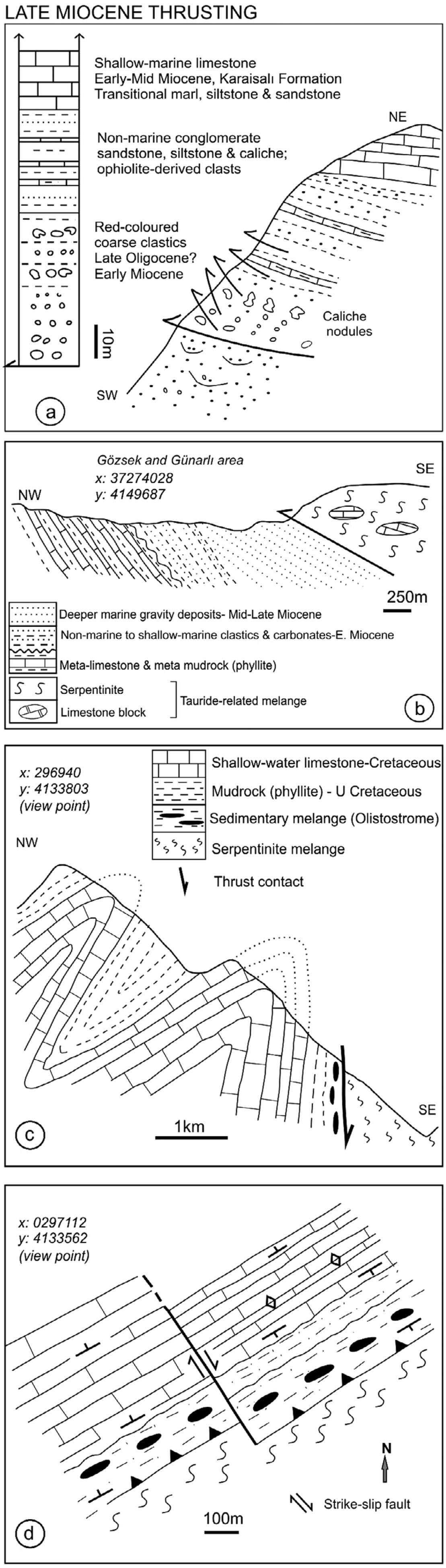

Figure 16. Local cross-sections showing deformation of inferred Late Miocene-Pliocene age. (a) Internal imbrication of Miocene sequence. Mid-Miocene marine siliciclastic succession is overthrust by an Early Miocene non-marine sediments passing upwards into shallow- marine carbonates. Yenicekale area; NW of Amanos Mountains; (b) Meta-carbonate and phyllite (Late Cretaceous) transgressively overlain by Early Miocene non-marine clastic sediments, which are in turn unconformably overlain by Mid-Miocene fining-and deepening-upwards siliciclastic marine sediments. The Miocene succession is overthrust by melange related to the Tauride allochthon. Gözsek and Günarlı areas, 11 km SW of Yenicekale, NW of Amanos Mountains; (c) Large-scale SE-vergent folds in Mesozoic shelf carbonates and overlying melange; W of Türkoğlu; (d) Transverse fault occurred in frontal area of the large-scale folds.

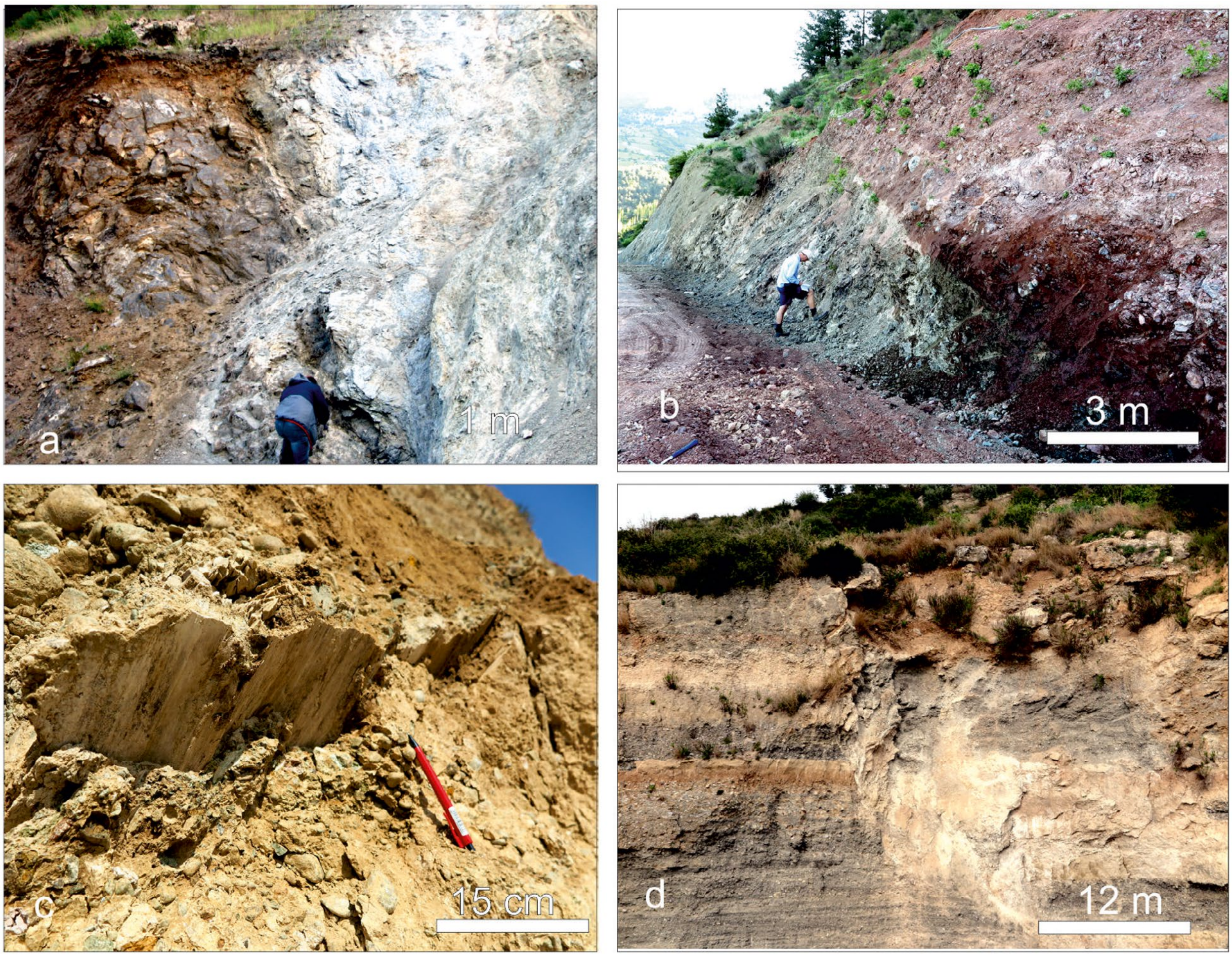

Figure 17. Field photographs of outcrop-scale faults; (a) Palaeozoic metaclastic sedimentary rocks in reverse fault contact with serpentinite, 3 km WSW of Kaledibi; (b) Reverse fault separating Middle and Early Miocene sediments near the front of the Tauride allochthon, Yenicekale; (c) Normal faults cutting Pliocene deposits with slickensides, 8 km SW of İskenderun; (d) Sinistral-reverse strike slip (transpression) in Pliocene fluvial sediments, 6.6 km SW of Erzin.

for example, is well developed along a tens to-hundreds-of-metres wide, ca. N-S fault zone, exposed along the İskenderun to Hatay highway (southeast of Belen; Figure 15(c)). Three discrete classes of structure are present in this area: (1) Bedding-parallel and bedding-sub-parallel compression-related structures in the form of shear planes, small-scale duplexes and ramp structures. Associated asymmetrical brittle-style cylindrical folds that are mostly overturned to the east or southeast; (2) approximately E-W trending, high-angle faults (well exposed along a tens of-metres-high escarpment adjacent to the main road) are characterised by oblique-normal slickensides; (3) sub-vertical strike-slip faults which range from discrete shear zones (up to tens of metres wide) to widely distributed faults (Figure 13(b)).

Cross-cutting relationships, where locally developed in the south of the area, indicate that E-vergent compression-related thrusting was followed by the ca. E-W oblique-normal faulting, and then by ca. N-S strike-slip faulting. In addition, Eocene limestones further north, near Burgaçlı (W of Bahçe), show evidence of thrust-related deformation in the form of small-scale asymmetrical folds, low-angle brittle shear zones and duplex/ramp structures.

In the southern Amanos Mountains, the Paleogene limestones are faulted and deformed (Atan, 1969; Yiğitbaş et al., 1992; Yılmaz, 1984). We infer the existence of east-vergent folds on scales of tens of metres to kilometres. Specifically, the crest of the mountain range between İskenderun and Kırıkhan is dominated by an enormous N-S trending, east-vergent fold structure which is continuous longitudinally for tens of kilometres (Figure 14(f)). In addition, the Eocene limestones have undergone intense deformation, as observed along the southeastern margin of the range (N of Kırıkhan) in the vicinity of the EAF zone (Figure 9(c)).

Additional evidence comes from detailed mapping of a small rectangular area (ca. 5 km E-W by x 15 km N-S), ca. 5 km NW of Kırıkhan (Figure 3). In this area, ophiolite-related rocks that were emplaced during Late Cretaceous thrusting are reported to be depositionally overlain by two contrasting cover sequences. The first of these in the east is made up of Late Maastrichtian to Late Palaeocene shallow-water and reef limestones (Terbüzek and Besni-Eşmişek formations), whereas the other to the west (upper sheet) is characterised by pelagic limestone and 'flysch' of Late Cretaceous to Mid-Eocene age (Cona Group). In the south of the area the upper, westerly sequence is mapped as thrust eastwards over the lower, easterly sequence. Yılmaz (1984) inferred a major phase of thrusting during the late Middle Eocene that involved relatively long distance tectonic transport over the two contrasting approximately contemporaneous cover sequences, and that this represented the time of main shortening, thickening and ophiolite emplacement in the Amanos Mountain. On the other hand, assuming that the Eocene thrusting is accepted, the Paleogene basin is known to have been palaeogeographically diversified such that both neritic and pelagic sequences could have co-existed nearby (possibly as fault-controlled highs and lows) within a single intra-platform basin. Only relatively short-distance (several kilometres or less) thin-skinned thrusting would then be needed to juxtapose two contrasting Paleogene sedimentary sequences, without implications for the timing of ophiolite obduction, which was instead restricted to the Late Cretaceous. In addition, more work is needed to distinguish unambiguously Eocene and Miocene deformation events in areas such as Kırıkhan where Miocene cover sequences are locally absent.

4.4. Structure affecting Miocene sequences

Miocene lithologies, as exposed on the lower western flanks of the mountain range, are typically gently inclined and relatively undeformed. For example, in the far northwest (e.g. Fatmalı to Yenicekale area) the Early Miocene sequence dips gently (<20°) northwards away from the underlying Mesozoic and Palaeozoic rocks. Further south (from Bahçe to Burgaçlı), the dip increases to as much as ca. 75°. Further south again (e.g. near Hasanbeyli), the dip decreases to ca. 25°. In the southeast, near Kırıkhan, the Miocene sequence commonly dips to the southeast at up to 35° away from the range. In contrast, in a few places (e.g. from Hasanbeyli to Yarpuz) the Miocene dips at <20° towards the range (Figure 13(a)). In these areas, the sediments are deformed by generally south-verging open folds and are cut by numerous small extensional faults. High-angle strike-slip faults and reverse faults are also locally abundant (Figure 16(a); see Electronic Supplement, Figure 5).

In the southeast (Kırıkhan and Belen areas), the Miocene sequence and its substratum of Paleogene limestone and ophiolitic melange are folded into east-verging folds on scales of tens to hundreds of metres (Figure 15(d)), and locally offset by ca. N-S-trending faults. In this area, the Miocene sequence and the underlying units are strongly deformed along several N-S zones, up to several tens of metres wide.

In addition, the Miocene sequence in overthrust, again generally eastwards, by the Tauride allochthon (represented the Misis-Andırın Complex) (Yılmaz & Gürer, 1996; Robertson et al., 2004; Figures 16(a) and 17(b)).

4.5. Structures affecting Pliocene and Pleistocene sequences

The eastern margin of the Amanos Mountains in the Karasu Valley is cut by a zone of high-angle left-lateral strike-slip faults related to the EATF. In several areas, high-angle faults cut Pleistocene sedimentary or volcanic rocks (Figure 12). Non-marine sediments of inferred Pliocene-early Pleistocene(?) age that are exposed along the western margin of the range dip at angles of up to 20–30° and are affected by both normal faulting (Figure 17c) and oblique-reverse (transpressional) faulting (Figure 17d). Where locally exposed (near Fevzipaşa), the inferred Pliocene-early Pleistocene(?) sediments are deformed into an NNE-SSW-trending open syncline (orientated sub-parallel to the mountain front) which is in turn overlain by horizontal Quaternary basalt. In contrast, in the west, Pleistocene fluvial terraces and alluvial fan deposits are tilted towards the mountain front at angles of up to 10° (N of Osmaniye) and up to 25° (between Düziçi and İskenderun). The alluvium is cut by a series of ca. N-S trending strike-slip faults that have eroded to form subdued west-facing scarp (between Osmaniye and Düziçi) that are up to ca. 85 m high (e.g. in the Erzin area). Similar N-S trending strike-slip faults are widely distributed to the west of the EATF (e.g. in the Andırın and Düziçi areas) (Figure 12).

5. Discussion and synthesis

5.1. Sedimentary and structural development

From the combined geological evidence, five major tectonic phases are recognised affecting the Amanos Mountains: Late Triassic; Late Cretaceous; Late Eocene, Late Miocene-Pliocene and Late Pliocene-Quaternary (Figures 18 and 19).

5.1.1. Triassic rifting

The Triassic rifting is documented by the abrupt change from mixed siliciclastic-carbonate shelf deposition along the northern margin of Gondwana, to more varied accumulation including dolomitic and microbial carbonates and also organic-rich mudrocks. Such sediments characterise rifting during the Triassic throughout southern Turkey, as documented from many parts of the Taurus Mountains (e.g. Robertson et al., 2012 and references). The rifting took place during continental break-up to form the Southern Neotethys, as documented by evidence from the Levant continental margin further south, and elsewhere (e.g. Garfunkel, 1998, 2004; Robertson, Parlak et al., 2016; see above). In the relatively inboard

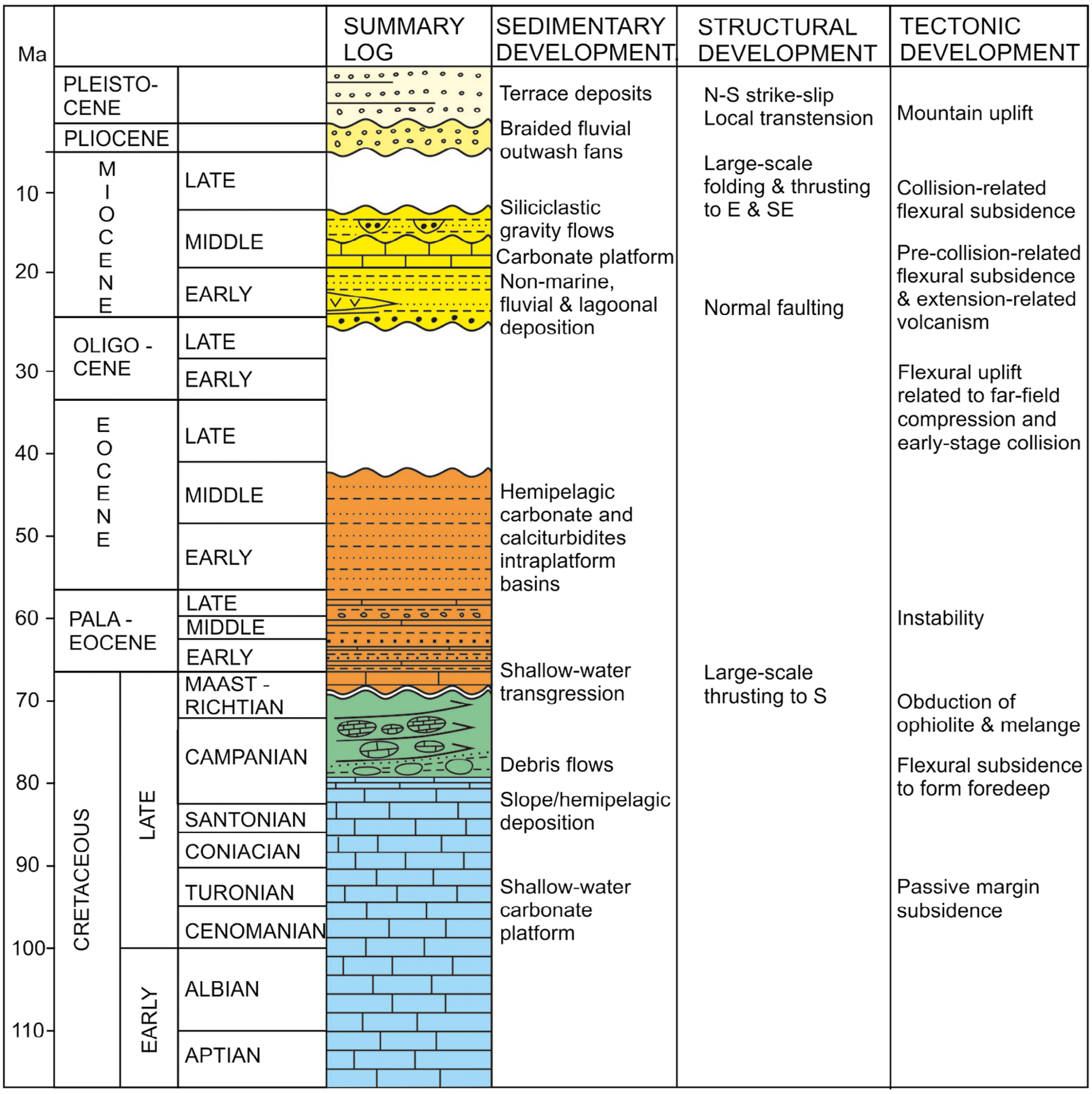

Figure 18. Time-activity diagram summarising the main sedimentary and structural features of the Amanos Mountains, together with tectonic interpretation. See text for discussion.

Amanos Mountain area, shallow-water deposition resumed on the stable, subsiding passive continental margin during Jurassic-Cretaceous time, as around the periphery of the Arabian plate generally (Sharland et al., 2001; Ziegler, 2001; Ziegler et al., 2001).

5.1.2. Late Cretaceous ophiolite emplacement

During the Late Cretaceous, ophiolitic rocks formed above a northward-dipping subduction zone within the Southern Neotethys (e.g. Robertson and Dixon, l984; Lytwyn & Casey, 1993; Robertson, 2002; Al-Riyami & Robertson, 2002; Al-Riyami et al., 2002; Parlak & Robertson, 2004; Chan, Malpas, Xenophontos, & LO, 2007; Parlak et al., 2009; Inwood et al., 2009b; Robertson et al., 2012; Karaoğlan et al., 2013). During Campanian-Maastrichtian time the subduction zone collided with the Arabian passive continental margin around the periphery of the Arabian continental margin, from the Eastern Mediterranean region to Oman (Glennie et al., 1973; Glennie, Bœuf, Hugues-Clarke, Pilaar, & Reinhardt, 1990; Yılmaz, 1990, 1993; Robertson, 2000; Akıncı et al., 2016; Robertson et al., 2016). Similar processes also affected the Amanos Mountains (Yılmaz et al., 1988; this study).

Recent work in the Adıyaman area, ca. 150 km east of the Amanos Mountains, indicates that the Koçali ophiolite and the associated Koçali melange were obducted onto the Arabian platform during Late Campanian to Mid-Maastrichtian time (Robertson, Parlak et al., 2016). Associated with the regional emplacement, the Troodos and Hatay ophiolites underwent ca. 90° anticlockwise rotation (Clube & Robertson, 1986; Inwood et al., 2009a; Morris, 1996). It is possible that the Amanos ophiolite also rotated similarly in view of its proximity to the Troodos-Hatay microplate.

5.1.3. Late Eocene compressional deformation

Shelf-carbonate deposition resumed locally in the Amanos Mountain area during the Maastrichtian, as in the Adıyaman area to the east and in many other areas of

TIME SCALE	STRUCTURE & TIMING	OCCURRENCE	INTERPRETATION
PLEISTOCENE SEDIMENTS	(dominant) (associated)	Normal faulting and tilting in W-central segment; strike-slip faulting seen in Pleistocene volcanics on both sides of Amanos Mountains.	Strike-slip related to strands of EAFZ on both sides of Amanos Mountains.
PLIOCENE SEDIMENTS	(dominant) (associated)	As above, with addition of ca. E-W reverse faulting along N margin of K. Maraş basin; NE of Amanos Mountains	As above, with the addition of compressional re-activation of ca. E-W Late Miocene thrust front
MIOCENE SEDIMENTS	Plio-Quaternary oblique (minor) Miocene (dominant) Early Miocene	Superimposed strike-slip faults, as above Localised oblique-normal faulting on W flank (continues into Pliocene?) Dominant large-scale folding and thrusting; vergence to S in the north; to the SE in the middle and to the E in the south. Minor normal fault in W of central area.	As above, superimposed collision-related compression swings from N-S to E-W southwards. Pre-collision flexural subsidence
MAASTRICHTIAN – EOCENE SEDIMENTS –	Plio-Quaternary Mid-Late Eocene	Superimposed strike-slip, as above Low-amplitude folding & reverse faulting; local small-scale duplexing	As above, superimposed S-directed regional compression pre-collision an early-stage collision
LATEST CRETACEOUS OPHIOLITE	Plio-Quaternary Late Miocene Latest Cretaceous (dominant)	Superimposed strike-slip, as above in NE, E (Karacasu Valley) and in S (Hatay area); Also Late Mesozoic folding in NE (Türkoğlu area); Dominant latest Cretaceous thrust emplacement	As above, P-Q strike-slip & Late Miocene deformation (in N) Ophiolite obduction.
LATEST CRETACEOUS MELANGES	Plio-Quaternary Late Miocene Late Cretaceous (dominant)	Superimposed strike-slip, as above Regional-scale folding; both flanks of mountain Thrusting, duplexing, isoclinal folding (ductile to brittle), layer-parallel extension; greenschist facies metamorphism	As above, P-Q strike-slip Late Miocene collisional deformation, as above. Compression-related melange emplacement.
MESOZOIC & PALAEOZOIC SEDIMENTS	Plio-Quaternary Late Miocene Middle Cretaceous Late Triassic	Superimposed strike-slip, as above Regional-scale folding and metamorphism Obduction-related deformation, as above Minor normal faulting (in N area)	with syn-sedimentary evidence of Triassic rifting

Obduction Duplexing Ductile deformation Brittle deformation Reverse faulting Normal faulting Strike-slip faulting

Figure 19. Summary of the main structures, as observed within seven discrete time slices that are separated by major stratigraphical or structural breaks.

the Arabian continental margin (see Robertson, Boulton et al., 2016; Robertson, Parlak et al., 2016). Carbonate debris-flow-type deposits within the Palaeocene-Early Eocene sequence in the southern Amanos Mountains are comparable within the similar-aged debris-flow units and slump sheets in the Adıyaman area (upper unit of the Germav Formation) and are indicative of regional tectonic instability (Robertson, Boulton et al., 2016). An important phase of compressional deformation affected the Amanos Mountains during the late Middle-Late Eocene, based on several lines of evidence: (i) Marine sedimentation halted and did not resume until the Late Oligocene(?)-Early Miocene; (ii) Paleogene sedimentary rocks are affected by open folding and reverse faulting, together with small-scale duplexing and possibly larger-scale thrusting in some areas, none of which are observed in the overlying Miocene sediments; (iii) The above structures verge generally southwards, in contrast to the dominantly eastward and southward vergence of the structures affecting the Miocene sequence (Figure 19).

Taking account of evidence from the Arabian foreland in SE Turkey, the deformation can be generally related to the initial collision of the Eurasian and Arabian plates (Boulton, 2009; Boulton & Robertson, 2007; Robertson, Boulton et al., 2016). The initial collision was preceded by crustal-up flexure, resulting in a regional unconformity and absence of preserved Oligocene sediments (Boulton, 2009; Boulton & Robertson, 2007; Hardenberg & Robertson, 2013; Robertson et al., 2004). The deformation could reflect far-field deformation related to suturing of the Neotethyan Ankara-Izmir-Erzincan ocean ('Northern Neotethys') in central Anatolia and/or initial closure of the Southern Neotethys (Robertson, Parlak et al., 2016).

5.1.4. Late Miocene crustal deformation

The Miocene sedimentary and structural record of the Amanos Mountain area reflects final collision of the Arabian and Eurasian plates, which took place progressively (Figure 20): (i) Flexural loading related to

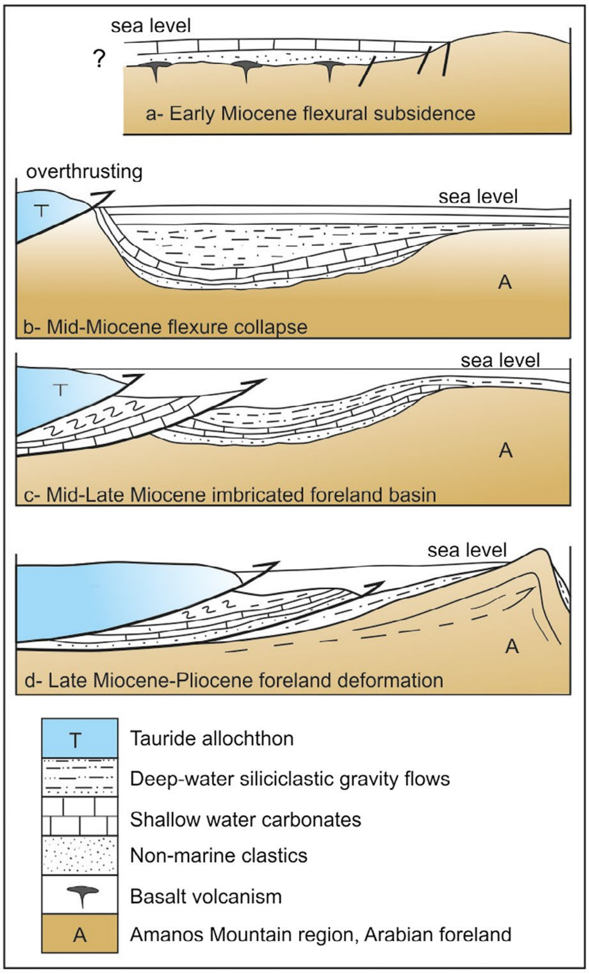

Figure 20. Tectonic-sedimentary model for Miocene-Pliocene deformation of the Amanos Mountain region. See text for discussion.

overthrusting of the Tauride continent to the north. This created accommodation space that was partially infilled by non-marine sediments, basaltic lava flows and then by transgressive shallow-marine carbonates during the Early Miocene; (ii) Flexural collapse ahead of the over-riding Tauride allochthon created a foreland basin. The resulting sedimentary accommodation space was infilled by siliciclastic gravity-flow deposits, sourced from the overthrusting Tauride continent; (iii) Final overthrusting by the Tauride allochthon, as documented to the NW, N and NE of the Amanos Mountains, where the Burdigalian-Langhian deep-water K. Maraş sedimentary basin was deformed and over-ridden by Tauride-related units. Similar overthrusting is seen to the N and NW of the Amanos Mountains (Yılmaz et al., 1988; Yılmaz & Gürer, 1996; Robertson et al., 2006; Gül et al., 2011; Akıncı et al., 2016); (v) Propagation of compressional deformation into Arabian foreland created up to mountain-sized folds, which are mainly SE-vergent in the north and central areas but E-vergent in the south (Figure 19).

5.2. Uplift of the Amanos Mountains compared to adjacent regions

Much recent research in the Eastern Mediterranean region focuses on the uplift of the Taurus Mountains (Bartol & Govers, 2014; Clark & Robertson, 2002; Clark et al., 2005; Cosentino et al., 2012; Jaffey & Robertson, 2005; Robertson, Parlak, & Ustaömer, 2009; Schattner, 2010; Schildgen, Cosentino, Bookhagan et al., 2012) and also of Cyprus to the south (Poole, Shimmield, & Robertson, 1990; Poole & Robertson, 1991; Kinnaird, Robertson, & Morris, 2011; Harrison et al., 2012; Kinnaird & Robertson, 2013; Main, Robertson, & Palamakumbura, 2016; Palamakumbura et al., 2016; Palamakumbura & Robertson, 2016; Figure 1). Utilising improved absolute age dating, it has recently been shown that the central segment of the Taurus Mountains bordering the easternmost Mediterranean Sea was largely uplifted during the Pleistocene (Schildgen, Cosentino, Bookhagan et al., 2012). This uplift has been explained by deep-seated crustal processes, possibly involving break-off or delamination of the African plate as it subducts beneath the Eurasian plate (Faccenna, Bellier, Martinod, Piromallo, & Regard, 2006; Keskin, 2003; Schildgen, Cosentino, Caruso et al., 2012; Şengör, Özeren, Genç, & Zor, 2003). The Troodos massif of Cyprus is known to have uplifted during the Pleistocene (Kinnaird & Robertson, 2013; McCallum & Robertson, 1990; Poole et al., 1990), a process that has been related to the collision of the Eratosthenes Seamount with the Cyprus trench to the south of the island, combined with upward diapiric protrusion of the core of the Troodos ophiolite. In addition, based on recent dating results and field studies, the Kyrenia Range in the N of Cyprus has also uplifted during the Pleistocene (Figure 2; Palamakumbura et al., 2016; Palamakumbura & Robertson, 2016).

The timing of uplift of the Amanos Mountains is constrained by several lines of evidence: (i) Marine deposition on the east flanks of the Amanos Mountains ended during the Late Miocene (Figure 20(d)). The latest known marine deposition in the K. Maraş basin to the northeast is dated as Messinian (Hüsing et al., 2009); (ii) The western and far-southeastern areas of the mountain region are characterised by hundreds-of metres-thick coarse fluvial conglomerates of Pliocene-Pleistocene(?) age (Ulu, 2002b; see above). Outwash fans extended tens of kilometres away from the mountain flank in the west. The influx of very coarse material is explicable by intense uplift and deep erosion of the Amanos Mountains stratigraphy during the Pliocene-Pleistocene(?); (iii) A possible source of the quartz and mica in the Late Miocene sediments in the southeast (Kırıkhan area) is the Tauride allochthon to the north (e.g. Berit area) (Boulton, 2009). A more local origin from the Amanos Mountains Palaeozoic sequence is also possible, but there is no evidence a high-relief proximal source area until the Pliocene.

The sedimentary evidence implies that uplift and erosion of the mountains climaxed during the Pliocene-Early Pleistocene(?), followed by diminished coarse clastic sediment supply during the mid-late Pleistocene as the topography matured. The presence of relatively mature erosion profiles extending from the base to near the crest of the range (as observed in a relatively low saddle within the central mountains, E of Bahçe), suggests that the topography was becoming increasingly mature during the Pleistocene, with correspondingly decreasing runoff. During the Pleistocene, very coarse detritus mainly accumulated within up-to-several-kilometre-scale alluvial fans that issued from deeply eroded river valleys and stream courses along both flanks of the Amanos Mountains. Little of the coarse alluvial supply was retained near the eastern mountain front during the Pleistocene, probably owing to bypassing towards the Gulf of İskenderun (Figure 12).

In some areas near the western mountain front (e.g. Düziçi, Osmaniye, Erzin, Karayılan) the Pliocene and Pleistocene alluvial deposits are tilted towards the east, implying the presence of contemporaneous controlling normal faulting (although faults are not clearly exposed). The older alluvium of inferred Pliocene-Early Pleistocene(?) age is generally tilted to higher angles (20–25°) than the younger, better-dated Pleistocene alluvium (1520°) (Duman & Emre, 2013; this study). A possible explanation is that the Amanos Mountains began to undergo extensional (or transtensional faulting) during later Pleistocene time, especially in the west (i.e. incipient orogenic collapse). The normal faulting localised coarse Pleistocene alluvium close to the western range front unlike earlier during the Pliocene. Also, there is evidence of oblique-normal faulting within the mountain range (e.g. roadcut near Belen area) which post-dated the inferred Late Miocene compressional deformation. In contrast, in the east, within the EATF (Fevzipaşa area), locally exposed alluvial fan deposits of inferred Pliocene-Early Pleistocene(?) age underwent open folding parallel to the mountain front as a result of late-stage compression, and were later covered by horizontal Quaternary basalts.

5.2.1. Controls of uplift

The approximately N-S regional uplift of the Amanos Mountains took place within the northwesternmost part of the Arabian plate (Figures 2 and 3). Several aspects of the regional geology are relevant to the uplift.

(i) *Location due north of the N-S Levantine rifted continental margin*. To the south of the Amanos Mountain area the Southern Neotethys rifted in a ca. N-S direction during the Triassic, parallel to the Levant margin (Garfunkel, 1998, 2004). The locus of uplift of the Amanos Mountains is likely to have exploited the northward extension of this approximately N-S trending rift zone.

(ii) *Location at the intersection of two compressional lineaments*. The two lineaments that were active during the Late Miocene-Pliocene are the NW-SE trending central Tauride lineament and the ca. E-W-trending eastern Tauride lineament (Figures 2 and 3). The convergence of these two lineaments focussed shortening and uplift within the Amanos Mountain area.

(iii) *Location near the triple junction of the African, Arabian and Eurasian plates*. The Dead Sea Transform Fault (DSTF) is inferred to have extended northwards into southern Turkey along the Karasu lineament during the Early Pliocene (e.g. Garfunkel, 2014). The northward propagation of the DSTF involved a slight bend to the northwest (Figure 21), which could have resulted in localised transpression and uplift (Chorowicz et al., 1994; Adıyaman & Chorowicz, 2002; Westaway, 2004; see below). However, this effect is unlikely to have been a significant factor in the uplift of the Amanos Mountains because it affected a vast area including the mountains to the north and northeast of K. Maraş (e.g. Ahir Dağ) (Figures 3 and 4).

(iv) *Location near a zone of possible slab detachment*. The uplift of the south-central Anatolian Plateau has been linked to detachment of the downgoing African plate following continental collision, together with possible compensating mantle inflow (see Bartol & Govers, 2014; Birk Biryol, Beck, Zandt, & Özacar, 2011; Faccenna et al., 2006; Schildgen, Yıldırım, Cosentino, & Strecker, 2014 for alternatives). The potentially affected region extends across southern Turkey, including the Amanos Mountains. However, the Amanos Mountains are oriented ca. N-S generally at right angles to any detached slab, and they form an uplifted lineament in contrast to the southern part of the Anatolian Plateau as a whole. Also, the inferred Late Miocene-Pliocene Amanos Mountain uplift appears largely to predate major uplift of southern Anatolia. Although uplift of the Anatolian Plateau was active during the Late Miocene (Cosentino et al., 2012; Jaffey & Robertson, 2005), the main surface uplift appears to have taken place during the Pleistocene, as shown by evidence from several areas including the Mut Basin to the west (Schildgen, Cosentino, Bookhagan et al., 2012). The timing of uplift of the Amanos Mountains appears to be dissimilar to that of the Kyrenia Range, N of Cyprus, which occurred during the Pleistocene (Palamakumbura & Robertson, 2016; Palamakumbura et al., 2016), and probably relates to the collision of the Eratosthenes Seamount with the Cyprus trench to the south

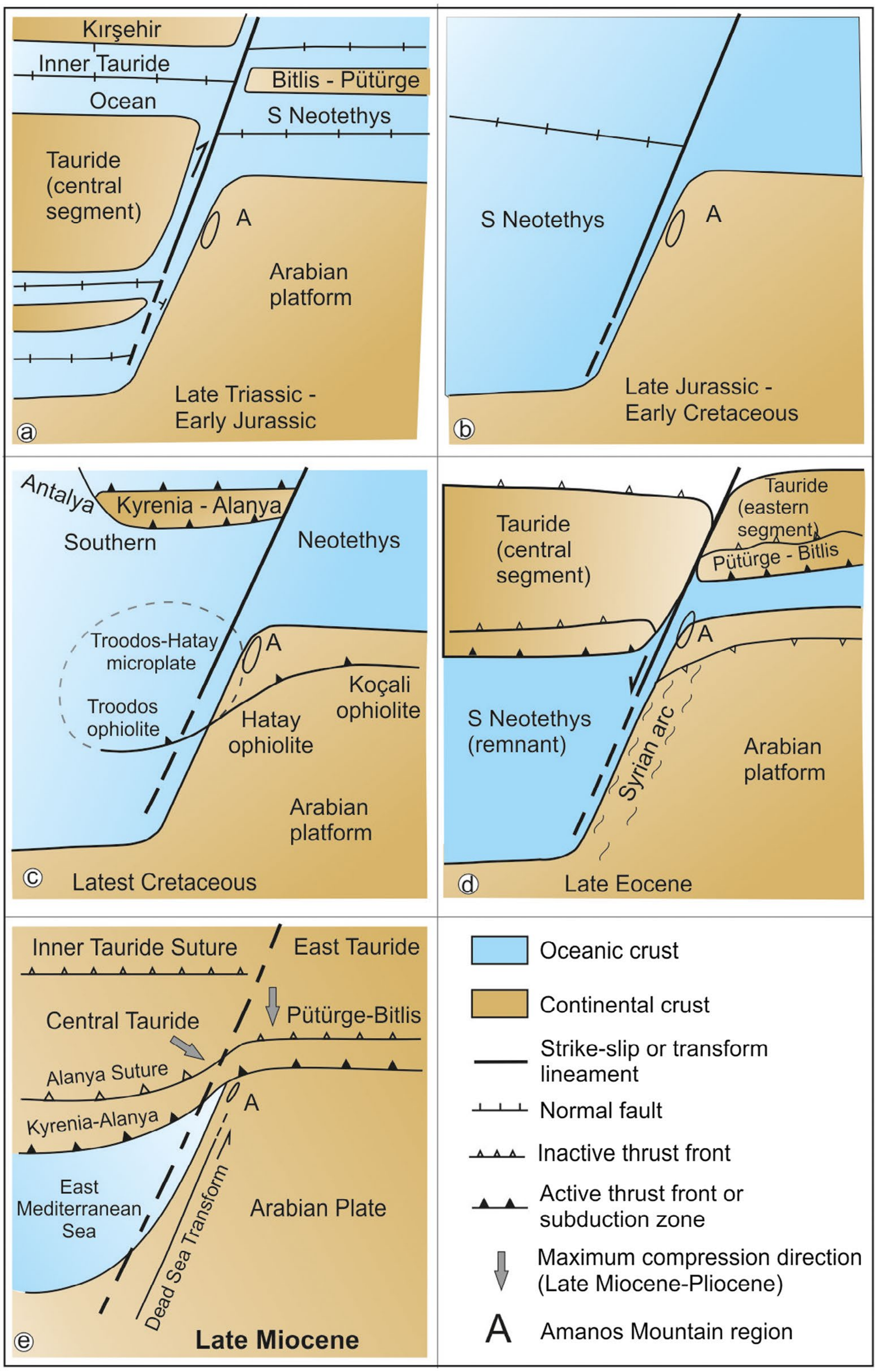

Figure 21. Plate tectonic sketch maps showing the tectonic development of the Amanos Mountain region (based on Robertson et al., 2012; see text for additional data sources). (a) Late Triassic-Early Jurassic rifting of Neotethys; (b) Late Jurassic-Early Cretaceous passive margin; (c) Latest Cretaceous northward subduction and ophiolite emplacement; (d) Late Eocene pre-collision/initial collisional setting; (e) Oligocene-Miocene final subduction of Southern Neotethys, convergence, foreland basin development, focussed compression and uplift (Late Miocene-Early Pliocene).

of Cyprus (see Kempler, 1998; Kempler & Ben-Avraham, 1987; Reiche, Hübscher, & Ehrhardt, 2015; Robertson, 1998).

The uplift of the Amanos Mountains appears to relate to two main factors. The first is likely be inherited basement weaknesses which were particularly exploited by deep-seated Late Miocene-Pliocene compression. The second relates to the focusing of convergent stress near the intersection of the two obliquely converging lineaments during Mid-Late Miocene time (western and eastern segments of the Tauride allochthon). Oblique,

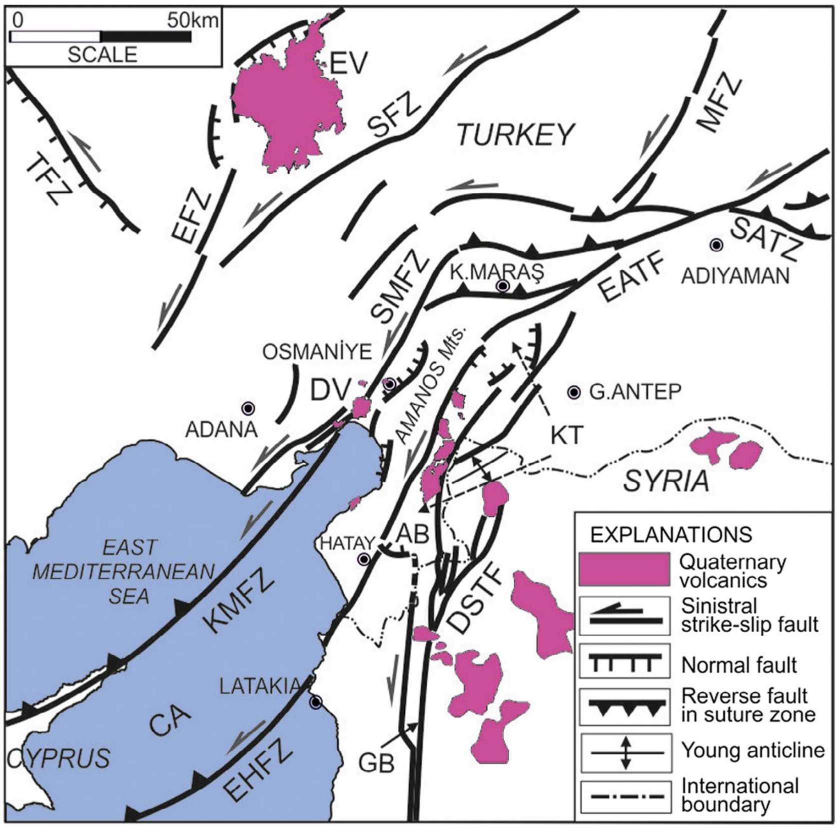

Figure 22. Main active tectonic lineaments during the Pliocene-Pleistocene post-collisional development of the region adjacent to the Amanos Mountain with Quaternary basalts added. The faults in Turkey are simplified from Emre et al. in press, whereas those in Cyprus and the Mediterranean Sea are based on Hall, Aksu, Calon, and Yaşar (2005) and Robertson et al. (2004). Faults related to the DSTF are simplified from Garfunkel (2014) and Westaway (2004). The distributions of basalts in Turkey and Syria are from Ulu (2002b) and from Ponikarov and Mikhailov (1986), respectively. Abbreviations: SAF, Sarız Fault; EFZ, Ecemiş Fault Zone; MF, Malatya Fault; TFZ, Tuzgölü Fault Zone; SMFZ, Sürgü-Misis Fault Zone; SATZ, Southeastern Anatolian Thrust Zone; EATF, East Anatolian Transform Fault; DSTF, Dead Sea Transform Fault; CA, Cyprus Arc; KMFZ, Kyrenia-Misis Fault Zone; EHFZ, Eratosthenes-Hatay Fault Zone; AB, Amik Basin; KT, Karasu trough. EM, Erciyes Volcano; DV, Delihalil Volcano; GB, Gahab Basin. Source: Authors

convergence can also explain why the uplift and deformation are most intense in the north, near the Tauride thrust front but then diminish southwards towards the Arabian platform. In summary, the inferred plate tectonic development from Late Triassic to Recent is shown in Figure 21.

5.2.2. Neotectonic 'escape tectonics' in the Amanos region

Reflecting the later stages of the African-Eurasian collision, the Anatolian microplate began to migrate westwards ca. 4 Ma ago, by means of lateral extrusion (Şengör, Görür, & Şaroğlu, 1985) or 'escape tectonics' (Burke & Sengör, 1986; Koçyiğit & Beyhan, 1998; Şengör & Kid, 1979), thus creating a fundamentally new kinematic organisation (e.g. Bozkurt, 2001; Le Pichon & Kreemer, 2010; Şengör et al., 1985; Figure 22). The left-lateral EATF is inferred to have become active during the Late Pliocene-Pleistocene (e.g. Herece, 2008; Şaroğlu, Emre, & Kuşcu, 1992; Westaway, 1994) and to have propagated southwards along the western margin of the Amanos Mountain compression zone until it linked with, or overlapped, the DSTF. In the NE, the Miocene suture zone is cut obliquely by faults related to a regional-scale releasing bend. To the south, the EATF runs through the Hatay depression (Hatay graben) and then extends as a convergent margin to the SE and S of Cyprus (Figure 2). The existence of normal faults within the Karasu trough imply that transtension-related processes have an important influence on the structural evolution of the Karasu Valley (Boulton, 2013; Boulton & Robertson, 2008; Duman & Emre, 2013). Both flanks of the Amanos Mountains (Karasu Valley and Osmaniye-Düziçi area) (Figure 22) are characterized by Quaternary basaltic rocks which are locally cut by relatively recent strike-slip faults. In addition, the left-lateral, transtensional Sürgü-Misis Fault Zone (SMFZ) became active in the vicinity of the western flank of the Amanos Mountains (SW section), extending southwards offshore into the Kyrenia-Misis Fault Zone (KMFZ). The SMFZ appears to have reactivated some pre-existing Miocene compressional structures where these have a suitable trend and dip (e.g. Duman & Emre, 2013).

The neotectonic period in the Amanos Mountain region was, therefore, characterised by a regional change from mainly compression during the Late Miocene-Pliocene to mainly transtension during the Plio-Quaternary. As a result, the Late Miocene-Pliocene Amanos mountain region experienced a progressive change from a compression to transtension/strike-slip zone related to the EATF. Simultaneously the DSTF propagated northwards until the two fault systems kinematically linked within the Karasu Valley area, although the exact nature and location of this linkage is uncertain. This new linkage, in turn, accommodated relative southward displacement of the Arabian sub-plate (i.e. Levant crust) and allowed the Karasu trough to form as a regional-scale ca. N-S depression. The largest depressed area, the Amik Basin in the south, is variously interpreted as a releasing bend, pull-apart or triple junction (e.g. Boulton et al., 2006; Duman & Emre, 2013). The associated strike-slip/transtension triggered tilting of the Pliocene sediments and the regional basaltic volcanism around the Amanos Mountains (e.g. Duman & Emre, 2013; Tatar, Piper, Gürsoy, Heimann, & Koçulut, 2004).

6. Conclusions

(1) The N-S trending Amanos Mountain lineament preserves a remarkable geological record of the northwesternmost corner of the Arabian plate, from Cambrian to Recent, adjacent to the Southern Neotethys ocean. Rifting, passive margin development, oceanic crust emplacement and multistage collision history all had a fundamental influence on the geological development of the Amanos Mountains. The most recent influence (<4 Ma) relates to the westward tectonic escape of the Anatolian microplate towards the Aegean region.

(2) Palaeozoic accumulation on a subsiding continental platform along the northern margin of Gondwana was disrupted by Triassic Neotethyan rifting, after which shallow-water carbonates accumulated on a subsiding platform until the Late Cretaceous.

(3) During the latest Cretaceous, ophiolitic rocks of inferred supra-subduction zone origin, together with accretionary melange and broken formation, were emplaced southwards over the flexurally collapsed carbonate platform.

(4) The Late Cretaceous allochthon was transgressed by shallow-marine carbonates during the Maastrichtian, deepening upwards into hemipelagic carbonates and calciturbidites during the Palaeocene-Eocene.

(5) Late Palaeocene-Middle Eocene (Lutetian) was characterised by tectonic instability, followed during the Late Mid to Late Eocene by south-vergent compression, open folding, reverse-faulting and local-scale duplexing, which are all interpreted as the effects of initial continental collision in the region.

(6) Early-stage collision also resulted in tilting, subaerial erosion, basaltic volcanism and shallow-marine carbonate deposition during the Early Miocene, as documented around the periphery of the Amanos Mountains.

(7) More advanced collision was accompanied by generally southward thrusting of Tauride continental crust causing flexural collapse and the creation of an Early Miocene deep-water foreland basin in the Amanos Mountain region.

(8) As collision intensified, the central and eastern segments of the Tauride allochthon (trending NE-SW and E-W, respectively), converged on each other, focussing compression in the Amanos Mountain region (i.e. inward-facing convergence).

(9) The propagation of compression through the Amanos Mountain region resulted in the formation of up to kilometre-sized, SE to E-verging folds and related thrust faults during the Late Miocene-Early Pliocene time. Deformation was most intense in the north and decreased southwards towards the Arabian platform as stress waned in this direction.

(10) Stratigraphic and other constraints indicate that related surface uplift climaxed during the Pliocene-Early Pleistocene(?).

(11) The collision-related uplift of the Amanos Mountains is interpreted as mainly relating to the interplay of two factors: i) Re-activation of a pre-existing ca. N-S zones of crustal weakness (possibly inherited from Triassic rifting); ii) stress focussing effects of two obliquely converging Tauride thrust lineaments during Late Miocene-Early Pliocene time.

(12) Large-scale mountain uplift ended when the Eastern Anatolian and Dead Sea transforms linked kinematically along the Karasu Valley. This is likely to have triggered relative southward displacement of the Arabian sub-plate in the area and a corresponding switch to transtension, accompanied by basaltic volcanism. Such features are among the manifestations of the westward 'tectonic escape' of the Anatolian microplate towards the Aegean region.

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